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Monoammonium Phosphate: Effect on Flammability of Excelsior and Pine Needles

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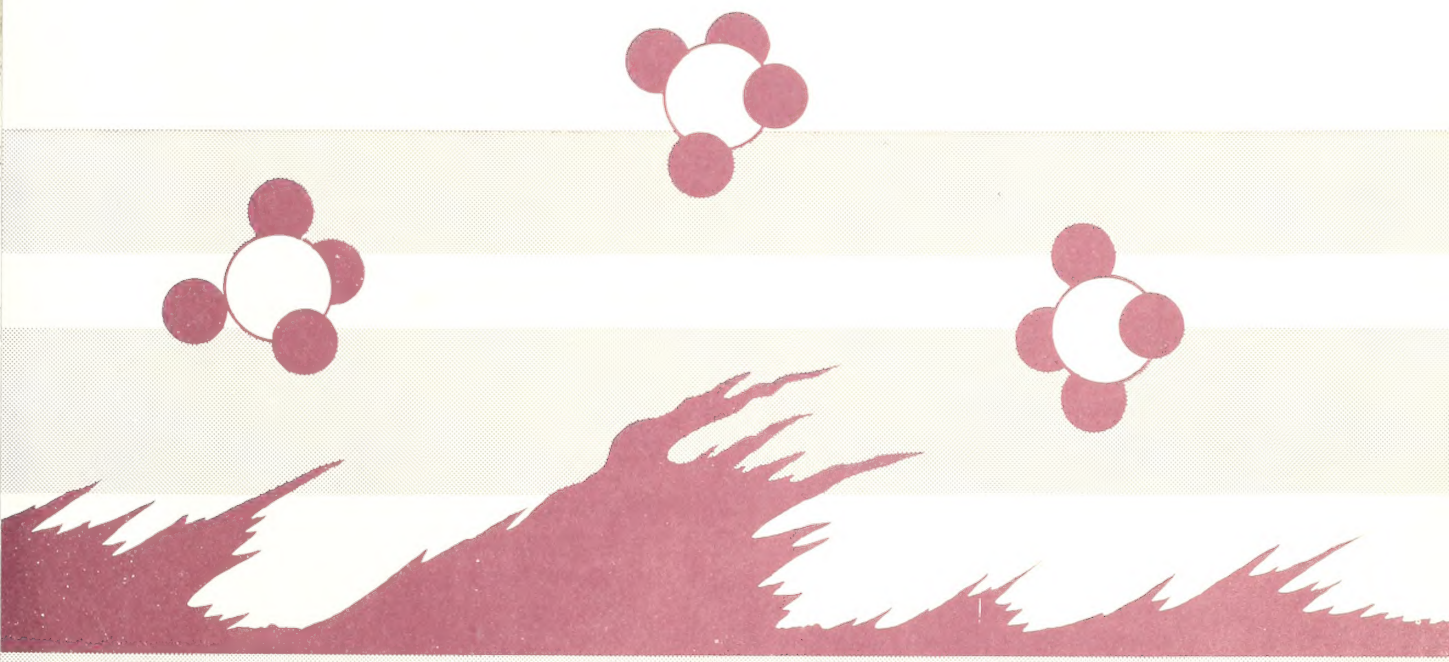

RESEARCH SUMMARY

Treated ponderosa pine needle and aspen excelsior fuel beds were burned to quantify the fire-retarding capabilities of five samples of monoammonium phosphates. The samples were the same except for their manufacturing processes, which could cause chemical impurities that may decrease combustion-retarding effectiveness. Treatment levels were normalized by converting to phosphate equivalents when comparing effectiveness. To obtain about equal penetration, approximately 0.26 gal (1 liter) of a solution containing one of the chemicals was applied to each bed. Different chemical treatment levels were obtained by varying the solution concentrations. Solutions were sprayed onto the fuel beds from a fan-type nozzle, and after drying completely, the fuel was burned in a 5-mi/h (8-km/h) wind at 90° F (32.2° C) and 20 percent relative humidity. Analysis of covariance and percent reduction in combustion rates were methods used to compare levels of effectiveness. Test results indicate no significant differences between the combustion-retarding abilities of the five monoammonium phosphates, and all proved to be as effective as standard diammonium phosphate when compared at equivalent phosphorous application levels.

THE AUTHOR

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Monoammonium Phosphate: Effect on Flammability of Excelsior and Pine Needles

Aylmer D. Blakely

INTRODUCTION

Forest fire retardants were first operationally delivered by aircraft in the mid-1950's, and consisted mainly of chemicals that retained water and amassed thick layers on aerial fuels. The first chemical to be used extensively was sodium-calcium borate (commonly called "borate") that not only thickened the water, but had some fire-retarding properties when dry (Miller and Wilson 1957). Borate was toxic to plants, erosive on pumps, and costly because of the required mix ratio. Bentonite clay was introduced to overcome some of the problems caused by borate, but it only thickened the water and had no long-term retarding properties when dry (Phillips and Miller 1959). Borate and bentonite use was phased out when chemicals (called long-term retardants) were introduced that more effectively retard combustion, even when completely dry.

Experiments with long-term chemicals were performed by Truax (1939) to quantify the fire-retarding abilities of water solutions of several commonly used chemicals and chemical combinations, and to determine the feasibility of using them on wildfires. These were some of the same chemicals that had been used successfully for impregnating and fireproofing building materials since the early 1900's. Studies by Truax and later by Tyner (1941) showed that diammonium and monoammonium phosphate water solutions were the most effective for retarding combustion. Other phosphate compounds have been tested, but the ammonium phosphates are the most chemically available for affecting pyrolysis. George and others (1977) reflect that phosphate compounds formed with Fe, Ca, or Mg usually are ineffective because of their high temperature requirements for decompositions and thus their unavailability in terms of altering pyrolysis and combustion reactions. Operation Firestop (1955a, 1955b) tested some phosphate chemicals along with borate, but because of the test methods and interpretation of results, borate was considered the superior fire-retarding chemical, and thus its use as the original aerial-delivery fire retardant.

Monoammonium phosphate (MAP) was dropped from a TBM airtanker onto forest fires in Georgia (Johansen 1959) with good results. Soon after, attempts were made to thicken the MAP with clays or gums (Johansen and Shimmel 1963) for better adherence to aerial fuels. Use of MAP was abandoned when Pyro, a liquid mixture of ammonium phosphate species, was introduced in the Southeast (Johansen and Crow 1965). Pyro was comparatively inexpensive and required only dilution with water and pumping into the airtanker. MAP was considered unhandy because it required breaking bags open and mixing with water under agitation. Later developments of mixing equipment resolved most of the limiting mixing procedures.

In 1961 tests were performed (Hardy and others 1962) to compare the effectiveness of several different retardant formulations that were being suggested and introduced by firefighters and chemical companies. Among those chemicals were borate, algin-gel, diammonium phosphate (DAP) thickened with algin and pectin, and ammonium sulfate thickened with attapulgite clay. The tests showed that the sulfate- and phosphate-based materials were superior to borate and water thickeners, especially after all the water had evaporated. Fire-Trol® (formulated with ammonium sulfate and clay thickener) and Phos-Chek® (formulated with diammonium phosphate and gum thickener) brand fire retardants were first produced commercially about 1962, and formulations containing various dry chemical combinations have since been the principal fire retardants used in the United States for combating wildfires. Several studies have been conducted to better quantify the combustion-retarding effectiveness of sulfates and phosphates, and to identify their basic fire-retarding mechanisms (George and Susott 1971; George and Blakely 1972; Browne and Tang 1963; and Eickner 1962). Other phosphate-based retardants have since been used extensively: Pyro, previously mentioned, and Fire-Trol 931, made of 10-34-0 ammonium polyphosphate (Wood 1970; George 1971; George and others 1977).

In recent years, many of the chemicals used to prepare retardant formulations—basic retardant chemicals as well as additives for coloring and corrosion inhibition—have increased severalfold in price and, in some cases, have become difficult or impossible to obtain. For example, for several years the DAP used in retardants was produced as a byproduct from the conversion of coal to coke. Phosphoric acid (H_3PO_4) was used to remove (scrub) ammonia bearing-off gases from manufacturing effluents. In this reaction, either mono- or diammonium phosphate is produced, but unfortunately, the cost of using these products has become prohibitive. MAP and DAP are also manufactured by bubbling ammonia gas through H_3PO_4. Much of the high cost of combining ammonia and acid is in the costs of ammonia or nitrogen (N); therefore, it is more economical to add only one ammonia (NH_3) to each phosphate (PO_4) to make $NH_4H_2PO_4$(MAP). In other cases, retardant users are searching for chemicals that are less expensive because of their formulas and/or manufacturing processes, but which are still cost-effective.

This study quantified the fire-retarding effectiveness of monoammonium phosphate chemicals from different sources and compared their effectiveness to diammonium phosphate (the basic fire retardant chemical in some currently approved retardants). Tests were performed with five MAP samples manufactured by various companies and/or processes.

The samples were basically the same except for minor differences in composition and manufacturing process. The chemicals and their apparent differences are:

- M-MAP – Fisher Scientific, ACS grade, granular form. Contains less than 0.03 percent impurities.
- S-MAP – Technical grade, granular form. Produced from technical grade phosphoric acid (white acid process) that has been neutralized with anhydrous ammonia.
- D-MAP – Technical grade, crystalline form. Technical grade phosphoric acid neutralized by ammonia-rich gases that are given off by burning coal to make coke.
- T-MAP – Technical grade, crystalline form. Produced from technical grade phosphoric acid that has been neutralized with anhydrous ammonia. (T-MAP and S-MAP are manufactured by similar processes, but by different companies.)
- A-MAP – Technical grade, crystalline form. Manufactured from wet-process phosphoric acid and then repurified to produce a technical grade product with less than 0.1 percent of impurities.

The phosphate quantities were calculated as P_2O_5 equivalents to aid effectiveness comparisons because all MAP or DAP formulations should be equally effective if the phosphate (P_2O_5) in each (the principal fire-retarding element) is present and available in equal concentrations.

The study was an indirect way to determine if the manufacturing process, manufacturer, or quality of fire retardant chemical causes any reduced availability of the phosphorus at the precise time or temperature during pyrolysis when the retardant would have the needed effect (George and Susott 1971). Comparison of like quantities of different chemicals that are equally effective fire retardants will indicate how much added chemical is necessary to increase the total available phosphorus in a particular chemical formula. All effectiveness data are compared to DAP because it has been used as a standard of comparison since 1970 (George and Blakely 1972).

STUDY METHODS

Fuel Beds

Combustion-retarding effectiveness data were gathered by burning mat-type fuel beds treated with different retardant chemicals. Two fuels were used for the study—ponderosa pine needles and aspen excelsior. The pine needles, gathered locally, were cleaned of debris, grass, and sticks, and stored to dry. The excelsior was ordered in compact bales that were pulled apart and allowed to come to equilibrium moisture content under inside conditions. The two fuels were used to determine the fire-retarding effectiveness of chemicals on fuels with a high cellulose (42 percent) and a low crude fat (1 percent) content (excelsior), and fuels with a low cellulose (18 percent) and a high crude fat (10 percent) content (needles). These fuels were not necessarily used to duplicate natural wildfire conditions, but because they (1) are relatively easy to obtain, (2) respond to temperature and humidity changes, (3) are similar in chemical content to many fuels encountered on wildland fires, and (4) provide predictably reproducible fires under controlled environmental and fuel moisture conditions.

Standard techniques were used (George and Blakely 1972) for constructing and treating the 8-ft- (2.44-m-) long, 3-inch-(7.62-cm-) deep, 18-inch- (45.72-cm-) wide fuel beds. Each pine needle bed contained 6 lb (2.72 kg) of fuel, and each excelsior bed contained 4 lb (1.81 kg) of fuel. The fuel moisture content (measured by xylene distillation) was between 4 and 5.5 percent for excelsior, and 6 and 7.5 percent for needles after preconditioning and before chemical treatment application.

Adjustments for Differences in Untreated Fuel Burning Rates

The burning characteristics of different batches of untreated fuels have varied somewhat in previous laboratory studies. Pine needles gathered in the fall have combustion rates that differ from those gathered in the spring, and fall needles may vary slightly from year to year. The same is true of batches of commercially prepared excelsior that may vary somewhat in untreated flame spread rates and total weight-loss rate. Because of the variations in untreated fuels used in this study, adjustments were necessary to make burning data comparable. One method was to calculate the percentage that untreated fuel combustion rates for individual fires are reduced by each treatment. By this means, the differences in untreated burning rates (flame spread and fuel bed weight loss) are taken into account and numerical comparisons can be made. A 0 rating indicates that a retardant has no effect on combustion, and a 100 rating indicates that a chemical totally stops flaming and glowing combustion. The percentage rating is calculated using the flame-spread rate and weight-loss rate for untreated and treated fuels (pine needles and aspen excelsior). For comparisons to be valid, treatment levels for different fires or chemicals must be approximately equal. Spread- and weight-loss rates for treated fuels are calculated as percentages of spread- and weight-loss rates for untreated fuels (percent reduction). Equal numbers of fires for each treatment level (or weighted averages) must be used if statistically meaningful percent reduction factors are to be averaged for two or more treatment levels.

Another method was to adjust each treated fuel burning rate by a percentage corresponding to the differences in average untreated burning rates for different batches of fuel. Recently used untreated fuels have burning rates varying from 5 to 17 percent higher than rates for untreated fuels used in the past when the DAP and M-MAP burns were conducted; therefore, in this study S-MAP burning rates have been adjusted downward. This adjustment also permits the use of the actual spread and weight-loss rates for computations and graphing, rather than conversion to percent reduction of untreated rates. Table 1 shows the untreated averages and the differences between needles and excelsior used in 1970 and 1980.

Table 1.—Factors for adjusting treated bed burning rates for differences in untreated burning rates

Year	Pine needles						Aspen excelsior					
	Average R/S[1]	Std. dev.	N	Average R/W[2]	Std. dev.	N	Average R/S	Std. dev.	N	Average R/W	Std. dev.	N
	Ft/min			*g/min*			*Ft/min*			*g/min*		
1980	2.03	0.10	4	345	3.0	4	4.26	0.10	4	529	35.1	4
1970	1.81	.03	12	294	3.3	11	4.04	.14	9	459	6.1	9
Difference	0.22			51			0.22			70		
	$1 - \frac{0.22}{2.03} = 0.892$			$1 - \frac{51}{345} = 0.852$			$1 - \frac{0.22}{4.26} = 0.948$			$1 - \frac{70}{529} = 0.868$		
Adjustment	0.892			0.852			0.948			0.868		

[1]R/S = flame spread rate
[2]R/W = burning fuel rate of weight loss

Chemical Application

A pressurized sprayer with a fan-shaped spray pattern was used to apply retardant (George and Blakely 1972). The sprayer was calibrated for each different retardant chemical and concentration to produce a spray pattern that would coat the fuels uniformly. The volume of chemical solution applied to each bed was held as closely as practical to 0.26 gal (1 liter), and the different levels of the dried chemical applied to different beds were varied by adjusting the solution concentrations. After treatment, fuel beds were dried under environmental conditions of 90° F ± 2° (32.2° C ± 2°), and 20 percent relative humidity ± 2 percent, until all the solution water had been evaporated and the fuel moisture content was about the same as before treatment. Low-velocity fans were used to keep air moving above the treated beds so drying would occur uniformly throughout the depth of the bed. After all the water had evaporated (determined by frequent weighing on an electronic balance), beds were burned in a wind tunnel under conditions of 90° F (32.2°), 20 percent relative humidity, and in a 5-mi/h (8-km/h) wind. (These environmental conditions can be related to wildfire situations by the following: When needles and excelsior are classed as fuel type U, the National Fire-Danger Rating System [NFDRS] grades fires in untreated fuels as spread component 5, energy release rate 38, and burning index 34.)

Burning Procedures

A 3-ft- (0.91-m-) long untreated fuel bed of the same fuel type and loading as that in the treated bed was ignited and allowed to burn into the treated fuel. As the fuel burned, the rate of weight loss was continuously measured by four load cells mounted beneath the bed (George and Blakely 1970), and data were recorded on a Tektronix® 4051 microcomputer. The flame spread was monitored visually, and an event marker was used to record the flame front progress. After each fire, the recorded data were entered into a computer program, and flame spread rate and total fuel bed weight loss rate were calculated and plotted. These two parameters were used for comparing the effectiveness of different chemicals and treatment levels.

RESULTS

About 250 treated and untreated beds were burned. Results of burning pine needles and aspen excelsior treated with DAP have been reported previously (George and Blakely 1972), and are used as a standard for USDA Fire Retardant Qualification Tests. The M-MAP-treated beds were burned during the same period as DAP-treated beds (George and Blakely 1972), and therefore untreated ponderosa pine and aspen excelsior from the same untreated fuel batches were used. (The M-MAP data have not been published previously.) The remaining fires were conducted using untreated fuels collected several years later. Adjustments were made (table 1) in the data for recent burns to compensate for differences in untreated burning rates. Tables for all MAP-treated (except M-MAP) beds contain columns of adjusted spread- and weight-loss rates that were used for regression analysis. These data and those for DAP and M-MAP are shown in tables 2 through 9.

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Table 2.—Summary of test data for DAP-treated aspen excelsior fuel beds (from George and Blakely 1972)

Treatment solutiom				Anhydrous chemical		Rate of flame spread R/S	Rate of weight loss R/W
Chemical by weight	Solution density	Solution quantity		DAP	P_2O_5		
Percent	*g/cm³*	*g*	*ml*	---- *g/ft²* ----		*Ft/min*	*g/min*
2.5	1.014	1000	986	2.08	1.12	3.01	200
2.5	1.014	990	976	2.06	1.11	2.96	320
2.5	1.014	970	957	2.02	1.09	3.12	225
2.5	1.014	985	971	2.05	1.10	2.82	296
5.0	1.029	1030	1001	4.29	2.31	1.51	188
5.0	1.029	950	923	3.96	2.13	1.33	213
5.0	1.029	990	962	4.12	2.22	1.01	126
5.0	1.029	936	910	3.90	2.10	1.27	143
5.0	1.029	917	891	3.82	2.06	1.16	170
7.5	1.042	1000	960	6.25	3.36	.61	114
7.5	1.042	980	940	6.13	3.30	.70	114
7.5	1.042	970	931	6.06	3.26	.72	133
7.5	1.042	1025	984	6.40	3.44	.39	51
10.0	1.056	1000	947	8.33	4.48	.61	71
10.0	1.056	995	942	8.29	4.46	.53	102
10.0	1.056	1040	985	8.67	4.66	.61	79
12.5	1.072	1030	961	10.73	5.77	.35	56
12.5	1.072	1010	942	10.52	5.66	.46	92
12.5	1.072	1005	938	10.47	5.63	.41	59

Table 3.—Summary of test data for DAP-treated ponderosa pine needle fuel beds (from George and Blakely 1972)

Treatment solutiom				Anhydrous chemical		Rate of flame spread R/S	Rate of weight loss R/W
Chemical by weight	Solution density	Solution quantity		DAP	P_2O_5		
Percent	*g/cm³*	*g*	*ml*	*---- g/ft² ----*		*Ft/min*	*g/min*
2.5	1.014	975	962	2.03	1.09	1.46	223
2.5	1.014	965	952	2.01	1.13	1.68	233
2.5	1.014	955	942	1.99	1.07	1.55	202
2.5	1.014	1000	986	2.08	1.12	1.70	196
5.0	1.029	1035	1006	4.31	2.32	1.56	205
5.0	1.029	995	967	4.15	2.23	1.27	160
5.0	1.029	990	962	4.12	2.22	1.08	169
5.0	1.029	1000	972	4.17	2.24	1.26	184
5.0	1.029	980	952	4.08	2.20	1.39	191
7.5	1.042	1000	960	6.25	3.36	1.36	180
7.5	1.042	1010	969	6.31	3.39	1.21	164
7.5	1.042	975	936	6.09	3.28	1.25	200
7.5	1.042	1025	984	6.41	3.45	.93	170
10.0	1.056	1020	966	8.50	4.57	82	163
10.0	1.056	995	942	8.29	4.46	69	174
10.0	1.056	1055	999	8.79	4.73	75	161
10.0	1.056	1010	956	8.42	4.53	94	196
12.5	1.072	1010	942	10.52	5.66	69	131
12.5	1.072	965	900	10.05	5.41	70	147
12.5	1.072	1050	979	10.94	5.89	43	111
15.0	1.084	1025	946	12.81	6.89	28	[illegible]
15.0	1.084	960	886	12.00	6.46	66	137
15.0	1.084	1000	923	12.50	6.73	50	129
15.0	1.084	990	913	12.38	6.66	35	101
17.5	1.108	1050	948	15.31	8.24	26	71
17.5	1.108	980	884	14.29	7.69	37	94
17.5	1.108	1015	916	14.80	7.96	39	97
17.5	1.108	1025	925	14.94	8.04	38	79
20.0	1.111	1005	904	16.75	9.01	33	76
20.0	1.111	1038	934	17.30	9.31	24	63
20.0	1.111	1081	973	18.02	9.69	29	--

Table 4.—Summary of test data for M-MAP-treated aspen excelsior fuel beds

Treatment solutiom				Anhydrous chemical		Rate of flame spread R/S	Rate of weight loss R/W
Chemical by weight	Solution density	Solution quantity		MAP	P_2O_5		
Percent	*g/cm³*	*g*	*ml*	*---- g/ft² ----*		*Ft/min*	*g/min*
2.5	1.014	1010	996	2.10	1.30	2.48	297
2.5	1.014	1010	996	2.10	1.30	2.63	294
2.5	1.014	995	981	2.07	1.28	2.23	264
5.0	1.029	1005	977	4.19	2.59	.57	113
5.0	1.029	1135	1103	4.73	2.92	.52	118
5.0	1.029	1055	1025	4.40	2.72	1.06	133
7.5	1.042	1030	988	6.44	3.98	.60	103
7.5	1.042	1100	1056	6.88	4.25	.68	79
7.5	1.042	1000	960	6.25	3.86	.73	120
10.0	1.056	930	881	7.75	4.78	.74	117
10.0	1.056	960	909	8.00	4.94	.43	82
10.0	1.056	965	914	8.04	4.96	.40	83

Table 5.—Summary of test data for M-MAP-treated ponderosa pine needle fuel beds

Treatment solutiom				Anhydrous chemical		Rate of flame spread R/S	Rate of weight loss R/W
Chemical by weight	Solution density	Solution quantity		MAP	P_2O_5		
Percent	*g/cm³*	*g*	*ml*	----- *g/ft²* -----		*Ft/min*	*g/min*
2.5	1.014	990	976	2.06	1.27	1.56	--
2.5	1.014	1035	1021	2.15	1.33	1.26	202
2.5	1.014	1040	1026	2.16	1.33	1.61	146
5.0	1.029	1035	1006	4.31	2.66	1.12	258
5.0	1.029	1090	1059	4.54	2.80	1.83	206
5.0	1.029	1045	1016	4.35	2.69	1.34	186
7.5	1.042	1070	1027	6.69	4.13	.74	94
7.5	1.042	1060	1017	6.63	4.09	.50	128
7.5	1.042	1070	1027	6.69	4.13	.70	147
10.0	1.056	1100	1042	9.16	5.65	.88	117
10.0	1.056	1135	1075	9.46	5.84	.73	134
10.0	1.056	965	914	8.04	4.96	.83	152
12.5	1.072	925	863	9.63	5.94	.50	87
12.5	1.072	940	877	9.79	6.04	.44	113
12.5	1.072	1040	970	10.83	6.69	.47	94
12.5	1.072	1085	1012	11.30	6.98	.47	91
12.5	1.072	1010	942	10.52	6.49	.43	80
12.5	1.072	1115	1040	11.61	7.17	.42	87
15.0	1.084	1125	1038	14.1	8.70	.45	120
15.0	1.084	1060	978	13.3	8.21	.47	123
17.5	1.108	1135	1024	16.55	10.22	.21	56
17.5	1.108	1115	1006	16.26	10.04	.34	59
17.5	1.108	1080	975	15.75	9.72	.25	54

Table 6.—Summary of test data for S-MAP-treated aspen excelsior fuel beds

Treatment solutiom				Anhydrous chemical		Rate of flame spread[1] R/S		Rate of weight loss[1] R/W	
Chemical by weight	Solution density	Solution quantity		MAP	P_2O_5				
Percent	*g/cm³*	*g*	*ml*	---- *g/ft²* ----		*Ft/min*		*g/min*	
2.5	1.014	992	978	2.06	1.28	2.53	2.40	216	187
2.5	1.014	988	974	2.06	1.27	2.41	2.28	223	194
2.5	1.014	1032	1018	2.15	1.33	1.79	1.70	171	148
5.0	1.028	1032	1004	4.30	2.65	.82	.78	--	--
5.0	1.029	1009	981	4.20	2.60	.70	.66	136	118
5.0	1.028	1041	1013	4.34	2.68	1.27	1.20	247	214
5.0	1.028	1076	1047	4.48	2.77	.98	.93	--	--
5.0	1.029	1022	994	4.26	2.63	.59	.56	134	116
7.5	1.042	1051	1009	6.57	4.05	.91	.86	223	194
7.5	1.042	1009	968	6.31	3.90	.80	.76	124	108
7.5	1.042	1034	992	6.46	3.99	.71	.67	137	136
10.0	1.056	1047	991	8.73	5.39	.46	.44	126	109
10.0	1.056	1061	1005	8.84	5.46	.58	.55	117	102
10.0	1.056	1046	991	8.72	5.38	.58	.55	58	50

[1]Adjusted for difference in untreated fuel burning rate

Table 7.—Summary of test data for S-MAP-treated ponderosa pine needle fuel beds

Treatment solutiom				Anhydrous chemical		Rate of flame spread[1] R/S		Rate of weight loss[1] R/W	
Chemical by weight	Solution density	Solution quantity		MAP	P_2O_5				
Percent	*g/cm³*	*g*	*ml*	*---- g/ft² ----*		*Ft/min*		*g/min*	
2.5	1.014	1009	995	2.10	1.30	1.78	1.59	244	203
2.5	1.014	985	971	2.05	1.27	1.52	1.36	259	221
2.5	1.014	985	971	2.05	1.27	1.88	1.68	251	214
2.5	1.014	995	981	2.07	1.28	2.25	2.01	212	181
2.5	1.014	1006	992	2.10	1.29	1.91	1.70	244	208
5.0	1.028	1024	996	4.27	2.63	1.40	1.25	200	170
5.0	1.028	1044	1016	4.35	2.69	1.57	1.40	209	178
7.5	1.042	1024	983	6.40	3.95	1.45	1.29	179	156
7.5	1.042	1031	989	6.44	3.98	1.29	1.15	206	176
7.5	1.042	1016	975	6.35	3.92	1.12	1.00	190	162
7.5	1.042	1038	996	6.49	4.00	1.11	.99	138	118
7.5	1.042	1060	1017	6.63	4.09	1.18	1.05	129	110
7.5	1.042	1024	983	6.40	3.95	1.07	.95	162	138
10.0	1.056	1021	967	8.51	5.25	.93	.83	167	142
10.0	1.056	980	928	8.17	5.04	.94	.84	129	110
10.0	1.056	1051	995	8.76	5.41	.86	.77	151	129
12.5	1.071	1032	964	10.75	6.64	.72	.64	159	135
12.5	1.071	1032	964	10.75	6.64	.82	.73	136	116
12.5	1.072	1060	989	11.04	6.82	.59	.53	.83	.71
12.5	1.072	1062	991	11.06	6.82	.47	.42	102	.87
15.0	1.084	1081	997	13.51	8.34	.52	.46	118	101
15.0	1.084	1152	1063	14.40	8.89	.48	.43	108	.92
15.0	1.084	1107	1021	13.84	8.54	.41	.37	.93	79

[1]Adjusted for differences in untreated fuel burning rates.

Table 8.—Summary of test data for treated aspen excelsior fuel beds

Chemical treatment	Treatment solutiom				Anhydrous chemical		Rate of flame spread[1] R/S		Rate of weight loss[1] R/W	
	Chemical by weight	Solution density	Solution quantity		MAP	P_2O_5				
	Percent	*g/cm³*	*g*	*ml*	*---- g/ft² ----*		*Ft/min*		*g/min*	
T-MAP	5.0	1.029	1046	1017	4.36	2.69	1.01	96	236	205
	5.0	1.029	1048	1018	4.37	2.70	94	.89	192	167
	5.0	1.029	1088	1057	4.53	2.80	.83	79	187	162
	10.0	1.059	1059	1000	8.83	5.45	.39	.37	97	.84
	10.0	1.059	1018	961	8.48	5.24	59	56	110	95
	10.0	1.059	1010	954	8.42	5.20	52	49	108	94
D-MAP	5.0	1.029	1054	1024	4.39	2.71	89	84	—	—
	5.0	1.029	1039	1010	4.33	2.67	91	86	178	155
	5.0	1.029	1059	1029	4.41	2.72	60	57	198	172
	10.0	1.059	1019	962	8.49	5.24	40	38	92	80
	10.0	1.059	1024	967	8.53	5.27	40	38	84	73
	10.0	1.059	1021	964	8.51	5.25	54	.51	95	82
A-MAP	5.0	1.029	1028	999	4.28	2.64	98	93	156	135
	5.0	1.029	1032	1003	4.30	2.65	72	68	144	125
	5.0	1.029	1010	982	4.21	2.60	.49	46	92	80
	10.0	1.059	1045	987	8.71	5.38	33	.31	88	76
	10.0	1.059	1049	991	8.74	5.40	.43	.41	134	116
	10.0	1.059	1021	965	8.51	5.25	.54	51	85	74

[1]Adjusted for differences in untreated fuel burning rates

Table 9.—Summary of test data for treated ponderosa pine needle fuel beds

Chemical treatment	Treatment solution: Chemical by weight	Treatment solution: Solution density	Treatment solution: Solution quantity		Anhydrous chemical: MAP	Anhydrous chemical: P_2O_5	Rate of flame spread[1] R/S		Rate of weight loss[1] R/W	
	Percent	*g/cm³*	*g*	*ml*	---- *g/ft²* ----		*Ft/min*		*g/min*	
T-MAP	5.0	1.029	1041	1012	4.34	2.68	1.54	1.37	188	160
	5.0	1.029	1033	1004	4.40	2.66	1.25	1.12	172	147
	5.0	1.029	1034	1005	4.31	2.66	1.33	1.19	204	174
	10.0	1.059	1005	949	8.38	5.17	.82	.73	140	119
	10.0	1.059	1032	975	8.60	5.31	1.09	.97	158	135
	10.0	1.059	1026	967	8.55	5.28	.98	.87	126	107
D-MAP	5.0	1.029	1008	980	4.20	2.59	1.65	1.47	190	162
	5.0	1.029	1050	1021	4.38	2.70	1.46	1.30	199	170
	5.0	1.029	1028	1000	4.28	2.64	1.51	1.35	233	190
	10.0	1.059	1033	976	8.61	5.31	1.13	1.01	--	--
	10.0	1.059	1053	995	8.78	5.42	1.07	.95	160	136
	10.0	1.059	1024	967	8.53	5.27	.84	.75	190	162
A-MAP	5.0	1.029	1037	1008	4.32	2.67	1.67	1.49	169	144
	5.0	1.029	1003	975	4.18	2.58	1.77	1.58	190	162
	5.0	1.029	1040	1011	4.33	2.67	1.41	1.26	202	172
	10.0	1.059	1044	986	8.70	5.37	1.01	.90	181	154
	10.0	1.059	1024	967	8.53	5.27	1.00	.89	168	143
	10.0	1.059	1026	969	8.55	5.28	.93	.83	203	173

[1]Adjusted for differences in untreated fuel burning rates.

In the George and Blakely (1972) study, DAP was tested at several treatment levels, and regression equations were determined for flame spread and weight loss rates on pine needles and aspen excelsior fuels. The same type regression analysis was used with M-MAP and S-MAP, and regressions for all three chemicals have been compared. The analysis was performed to determine if differences exist between the fire-retarding effectiveness of the three source-samples of P_2O_5. To perform statistical tests, it was assumed that there was no significant difference in overall effectiveness when equal levels of P_2O_5 were applied. The hypothesis was tested by covariance analysis and an "F" test.

Rates of flame spread and fuel weight loss (energy release) were fitted by a least-squares method to determine what equation form (quadratic, exponential, logarithmic, reciprocal, and so forth) would fit best and give high correlation coefficients.

Some of the best-fit equations shown in tables 10 and 11 do not have the highest R^2 values possible because data groups that were tested against each other required that their regression equations be of the same form (for example, all ponderosa pine rate-of-spread data are in a second-degree polynomial form so that "F" tests can be performed). (Equation use is limited to the range included in the data sets and extrapolations beyond the real data cannot be expected to predict accurately.) Three individual and three paired equations were formed with data for each chemical for each test parameter. Then data for all three chemicals (triplet) for each parameter were pooled, and another best-fit equation was formed. Each paired equation was tested against the triplet equations and each individual against each other individual equation by an "F" test method described in figure 1.

Table 10.—Regression equations for flame-spread rate and weight-loss rate for ponderosa pine needles

Treatment	N	Equation	R^2	F		Significance[2]
				Variance ratio		*Percent*
Rate of spread						
DAP	31	$Y = 1.9420 - 0.30426X + 0.01313X^2$	0.93			
M-MAP	23	$Y = 1.9419 - 0.31906X + 0.01543X^2$	.81			
S-MAP	24	$Y = 2.0152 - 0.29478X + 0.01255X^2$	.91			
Pooled						
DAP/M-MAP	54	$Y = 1.9523 - 0.31616X + 0.01471X^2$	.86	0.138	(3, 48)	NS
VS All-pooled				.76	(3, 48)	NS
DAP/S-MAP	55	$Y = 1.97073 - 0.29478X + 0.01213X^2$	.91	2.36	(3, 49)	NS
VS/All-pooled				2.64	(3, 49)	NS
M-MAP/S-MAP	47	$Y = 1.99750 - 0.31072X + 0.01410X^2$	.86	1.33	(3, 41)	NS
VS All-pooled				1.55	(3, 41)	NS
DAP/M-MAP/S-MAP	78	$Y = 1.97724 - 0.30872X + 0.01377X^2$	.86			
Rate of weight loss						
DAP	30	$Y = 234.18 - 18.002X$	.87			
M-MAP	22	$Y = 214.02 - 15.693X$	.83			
S-MAP	24	$Y = 217.77 - 16.471X$	.79			
Pooled						
DAP/M-MAP	52	$Y = 227.53 - 17.280X$	.85	.47	(2, 48)	NS
VS All-pooled				.47	(2, 48)	NS
DAP/S-MAP	54	$Y = 226.56 - 17.261X$	.84	1.94	(2, 50)	NS
VS All-pooled				2.09	(2, 50)	NS
M-MAP/S-MAP	46	$Y = 215.99 - 16.053X$	.82	.11	(2, 42)	NS
VS All-pooled				.51	(2, 42)	NS
DAP/M-MAP/S-MAP	76	$Y = 223.83 - 16.915X$	.84			

[1]Test for the reduction in variance between pooled and unpooled models
[2]All differences in regressions are not significant below the 99 percent level

Table 11.—Regression equations for flame-spread rate and weight-loss rate for aspen excelsior

Treatment	N	Equation	R^2	F		Significance[2]
				Variance ratio		*Percent*
Rate of spread						
DAP	19	$Y = -0.33231 + 3.5877\ (X^{-1})$	0.97			
M-MAP	12	$Y = -0.27498 + 3.4232\ (X^{-1})$	.92			
S-MAP	14	$Y = -0.05014 + 2.7322\ (X^{-1})$	.87			
Pooled						
DAP/M-MAP	31	$Y = -0.31400 + 3.5369\ (X^{-1})$	.95	0.14	(2, 27)	NS
VS All-pooled				1.12	(2, 27)	NS
DAP/S-MAP	33	$Y = -0.24474 + 3.3264\ (X^{-1})$	.94	4.19	(2, 29)	95
VS/All-pooled				4.21	(2, 29)	95
M-MAP/S-MAP	26	$Y = -0.16302 + 3.0786\ (X^{-1})$	.89	1.40	(2, 22)	NS
VS All-pooled				2.23	(2, 22)	NS
DAP/M-MAP/S-MAP	45	$Y = -0.25226 + 3.3512\ (X^{-1})$	.93			
Rate of weight loss						
DAP	19	$Y = 264.86 - 121.24\ (Ln\ X)$	.81			
M-MAP	12	$Y = 306.48 - 147.31\ (Ln\ X)$	.89			
S-MAP	12	$Y = 196.25 - 52.689\ (Ln\ X)$	.37			
Pooled						
DAP/M-MAP	31	$Y = 278.43 - 129.26\ (Ln\ X)$	.83	1.36	(2, 27)	NS
VS All-pooled				3.20	(2, 27)	NS
DAP/S-MAP	31	$Y = 241.43 - 96.375\ (Ln\ X)$	.65	3.74	(2, 27)	95
VS All-pooled				4.38	(2, 27)	95
M-MAP/S-MAP	24	$Y = 249.46 - 97.87\ (Ln\ X)$	.61	6.13	(2, 20)	99
VS All-pooled				6.57	(2, 20)	99
DAP/M-MAP/S-MAP	43	$Y = 257.21 - 108.64\ (Ln\ X)$	.70			

[1]Test for the reduction in variance between pooled and unpooled models
[2]All differences in regressions are not significant below the 99 percent level

Chemical 1,

N_1 points $f_1(x) = a_1 + a_2X + a_3X^2 \ldots a_pX^p$

Chemical 2,

N_2 points $f_2(x) = b_1 + b_2X + b_3X^2 \ldots b_pX^p$

Combine 1 and 2,

$N_1 + N_2$ points $f_3(x) = c_1 + c_2X + c_3X^2 \ldots c_pX^p$

Note: All three regressions must be of the same form; i.e., log, third degree polynomial, and so forth.

$$SS\dot{Y}_1 = \sum_{i=1}^{N_1} (y_1 i - f_1(x_i))^2$$

$$SS\dot{Y}_2 = \sum_{i=1}^{N_2} (y_2 i - f_2(x_i)^2)$$

$$SS\dot{Y} = \sum_{i=1}^{(N_1 + N_2)} (yi - f_3(x_i))^2$$

$SS\dot{Y} - SS\dot{Y}_1 - SS\dot{Y}_2$ = difference in $SS\dot{Y}$

$(N_1 + N_2 - P) - (N_1 - P) - (N_2 - P) = \rho$

$(SS\dot{Y}_1 + SS\dot{Y}_2) / (N_1 + N_2 - P) = MSE(\dot{Y})$

$$F(p, (N_1 + N_2 - 2)) = \frac{\text{Diff } SS\dot{Y}}{\rho} \Big/ MSE(\dot{Y})$$

Figure 1.—Method used to calculate F values.

The covariance analysis shows no significant difference between the fire-retarding effectiveness of any of the three chemicals except for one parameter. There appears to be a statistical difference between the regression for M-MAP and S-MAP on excelsior weight loss. The greatest differences are between data at the low treatment levels where small variations in treatment amounts or fuel moisture content will sometimes cause large-scale differences. (The curves show that fire retardant effectiveness is very sensitive to small changes within the low-treatment areas.) Examination of the M-MAP and S-MAP regression data shows that their curves cross at about the 3-g/ft^2 (929-cm^2) treatment level. Apparent differences within each separate regression for each chemical can be caused by variation in fuel chemical composition, environmental conditions, and retardant application. The apparent differences between the fire-retarding abilities of DAP, M-MAP, and S-MAP are because of these variations in testing procedures; and the apparent differences in total effectiveness are therefore not real but because of experimental error. When the three chemicals, two test parameters, and two fuel types are all combined, analysis indicates no real significant differences exist (at the 0.05 level) between the fire- retarding abilities of DAP, M-MAP, and S-MAP.

Two methods were used to evaluate D-MAP, A-MAP, and T-MAP. One method was to plot the individual points on the curves for pooled DAP/M-MAP/S-MAP (P_2O_5 curves) and make general comparisons. The other method was to calculate the flammability reduction percentage for each chemical and compare it to the reduction calculated for the same level of P_2O_5 from the pooled DAP/M-MAP/S-MAP equation. Tables 12 through 14 show the percent reductions for the different chemicals compared to reductions for pooled P_2O_5. The reductions compare closely for all chemicals with none varying more than 0.01 from the pooled P_2O_5 regression.

Table 12.—Reduction of untreated fuel combustion rates caused by D-MAP treatment[1]

		R/S % reduction		R/W	R/W % reduction		Cumulative % reduction	
P_2O_5	R/S	1	2		1	2	1	2
g/ft²	Ft/min			g/min				
				Ponderosa pine				
2.59	1.47	0.19	0.30	162	0.45	0.39		
2.70	1.30	28	.31	170	42	.39		
2.64	1.35	25	.30	190	35	39		
5.31	1.01	44	60					
5.42	.95	48	61	136	54	55		
5.27	75	.59	60	162	.45	54		
	Average	0.37	0.45		0.44	0.45	0.41	0.45
				Aspen excelsior				
2.71	0.84	0.79	0.76					
2.67	.86	79	.75	155	0.66	0.67		
2.72	57	86	76	172	63	68		
5.24	38	91	90	80	83	83		
5.27	38	91	90	78	85	83		
5.25	51	.87	.90	82	83	83		
	Average	0.86	0.83		0.74	0.75	.80	79
					Total average		0.61	0.62

[1]1 = percent reduction of combustion parameters (flame spread rate and weight loss rate) for untreated fuel bed rates.
2 = percent reducton of combustion parameters that are computed using equivalent treatment amounts and data (flame spread rate or weight loss rate) from pooled data curves for DAP, M-MAP, and S-MAP.

Table 13.—Reduction of untreated fuel combustion rates caused by A-MAP treatment[1]

		R/S % reduction		R/W	R/W % reduction		Cumulative % reduction	
P_2O_5	R/S	1	2		1	2	1	2
g/ft²	Ft/min			g/min				
				Ponderosa pine				
2.67	1.49	0.18	0.31	144	0.51	0.39		
2.58	1.58	.13	.30	162	.45	39		
2.67	1.26	30	.31	172	42	39		
5.37	901	50	60	154	48	55		
5.27	.89	51	60	143	51	54		
5.28	83	.54	.60	173	.41	54		
	Average	0.36	0.45		0.46	0.47	0.41	0.46
				Aspen excelsior				
2.64	0.93	0.77	0.75	135	0.71	0.67		
2.65	.68	83	.74	125	0.73	0.67		
2.60	46	89	74	80	83	.67		
5.38	31	.92	91	76	84	84		
5.40	41	90	91	116	75	84		
5.25	51	.87	.90	74	.84	.83		
	Average	0.86	0.83		0.78	0.75	.82	.79
					Total average		0.62	0.63

[1]1 = percent reduction of combustion parameters (flame spread rate and weight loss rate) for untreated fuel bed rates.
2 = percent reducton of combustion parameters that are computed using equivalent treatment amounts and data (flame spread rate or weight loss rate) from pooled data curves for DAP, M-MAP, and S-MAP.

Table 14.—Reduction of untreated fuel combustion rates caused by T-MAP treatment[1]

		R/S % reduction		R/W	R/W % reduction		Cumulative % reduction	
P_2O_5	R/S	1	2		1	2	1	2
g/ft²	Ft/min			g/min				
				Ponderosa pine				
2.68	1.37	0.24	0.31	160	0.46	0.39		
2.66	1.12	.38	.31	147	.50	.39		
2.66	1.19	.34	.31	174	.41	.39		
5.17	73	.60	.59	119	.60	.54		
5.31	.97	.46	.60	135	.54	.54		
5.28	.87	.52	.60	107	.64	.54		
	Average	0.42	0.45		0.53	0.47	0.48	0.46
				Aspen excelsior				
2.69	0.96	0.76	0.75	205	0.55	0.67		
2.70	.89	.78	.75	167	0.64	0.68		
2.80	.79	.80	.77	162	.65	.68		
5.45	.37	.91	.91	84	.82	.84		
5.24	56	.86	.90	95	.79	.83		
5.20	.49	.88	.90	94	.80	.83		
	Average	0.83	0.83		0.71	0.75	.77	.79
					Total average		0.63	0.63

[1] 1 = percent reduction of combustion parameters (flame spread rate and weight loss rate) for untreated fuel bed rates.
2 = percent reducton of combustion parameters that are computed using equivalent treatment amounts and data (flame spread rate or weight loss rate) from pooled data curves for DAP, M-MAP, and S-MAP.

Tables 10 and 11 show the results of regression analysis and "F" tests for regression differences. The program for calculating "F" values is given in figure 1. Figure 2 shows all the weight-loss data on excelsior for DAP, M-MAP, and S-MAP, and the pooled equation is plotted. Figure 3 shows data and the equation for spread rate data on excelsior for DAP, M-MAP, and S-MAP. Figures 4 and 5 are weight-loss and spread-rate data on pine needles for all three chemicals. Figures 6 through 9 show all data points for all three chemicals, and individual best-fit equations are plotted for each chemical.

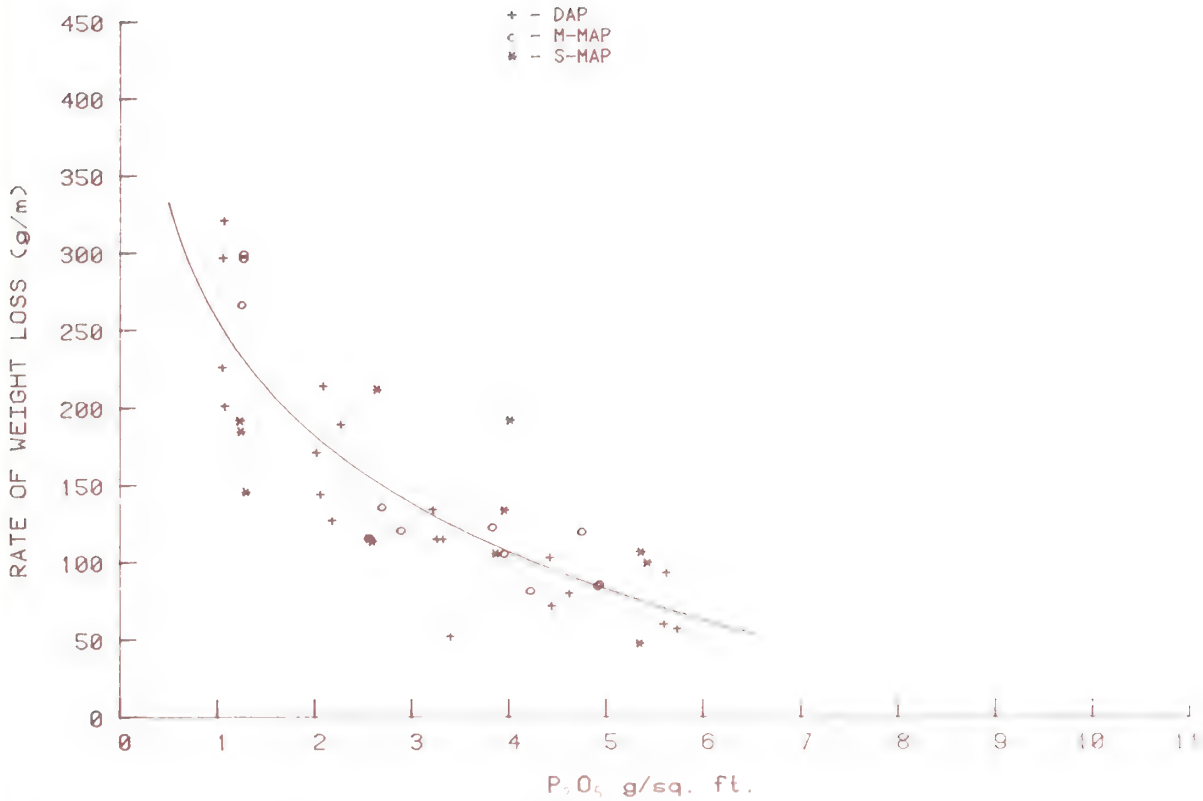

Figure 2.—Effect of DAP, M-MAP, and S-MAP on weight loss rate of excelsior. (Equation for pooled data is plotted.)

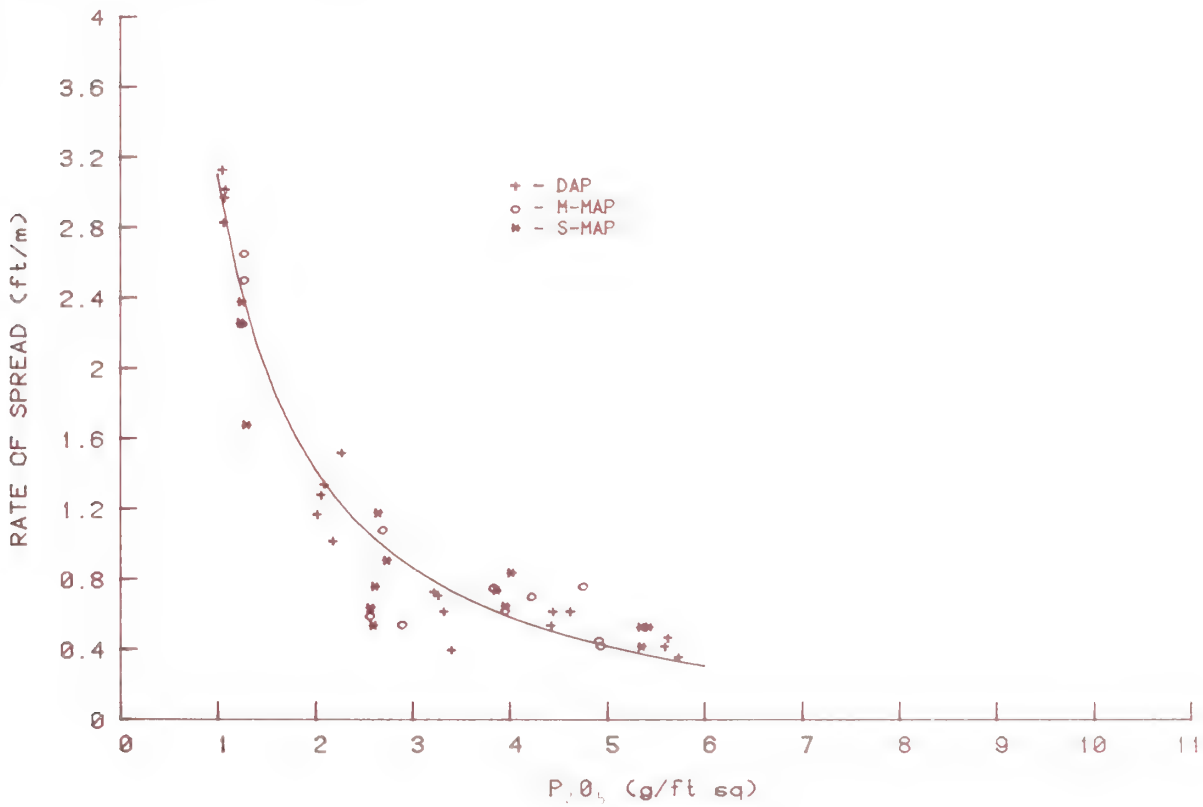

Figure 3.—Effect of DAP, M-MAP, and S-MAP on spread rate of excelsior. (Equation for pooled data is plotted.)

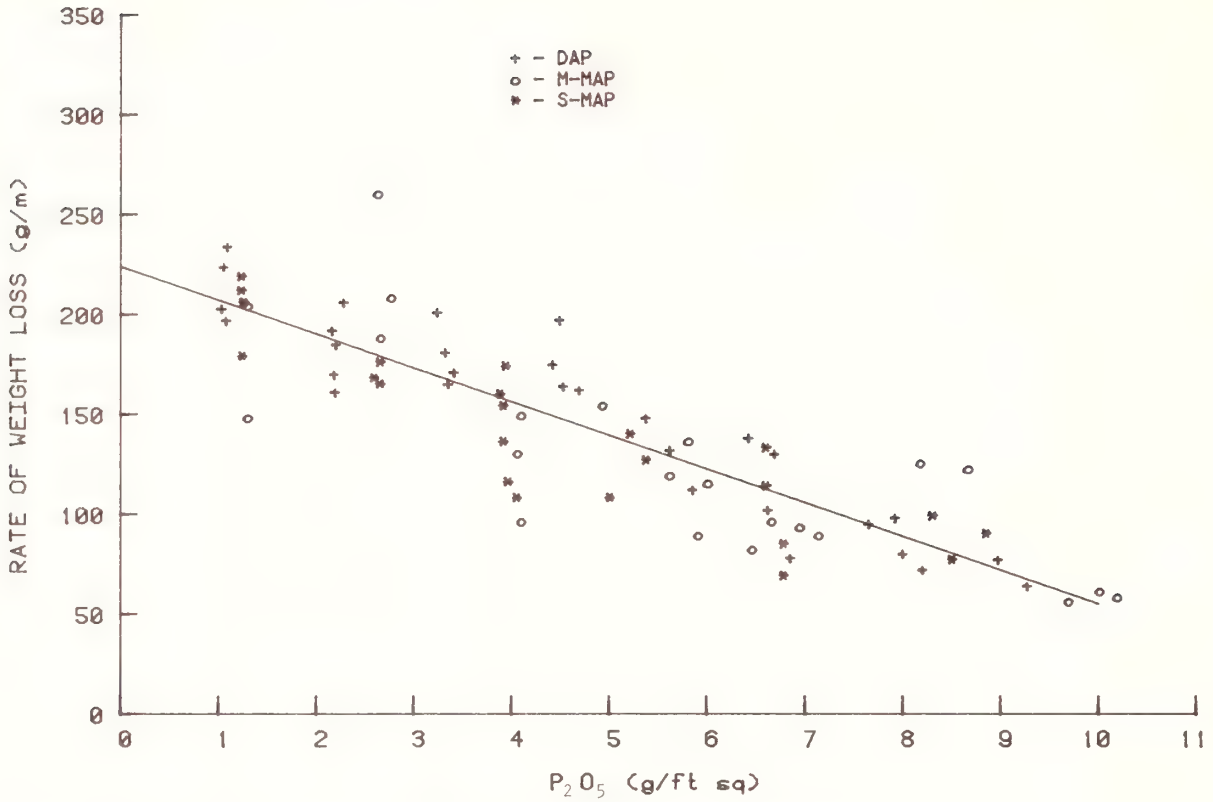

Figure 4.—Effect of DAP, M-MAP, and S-MAP on weight loss rate of pine needles. (Equation for pooled data is plotted.)

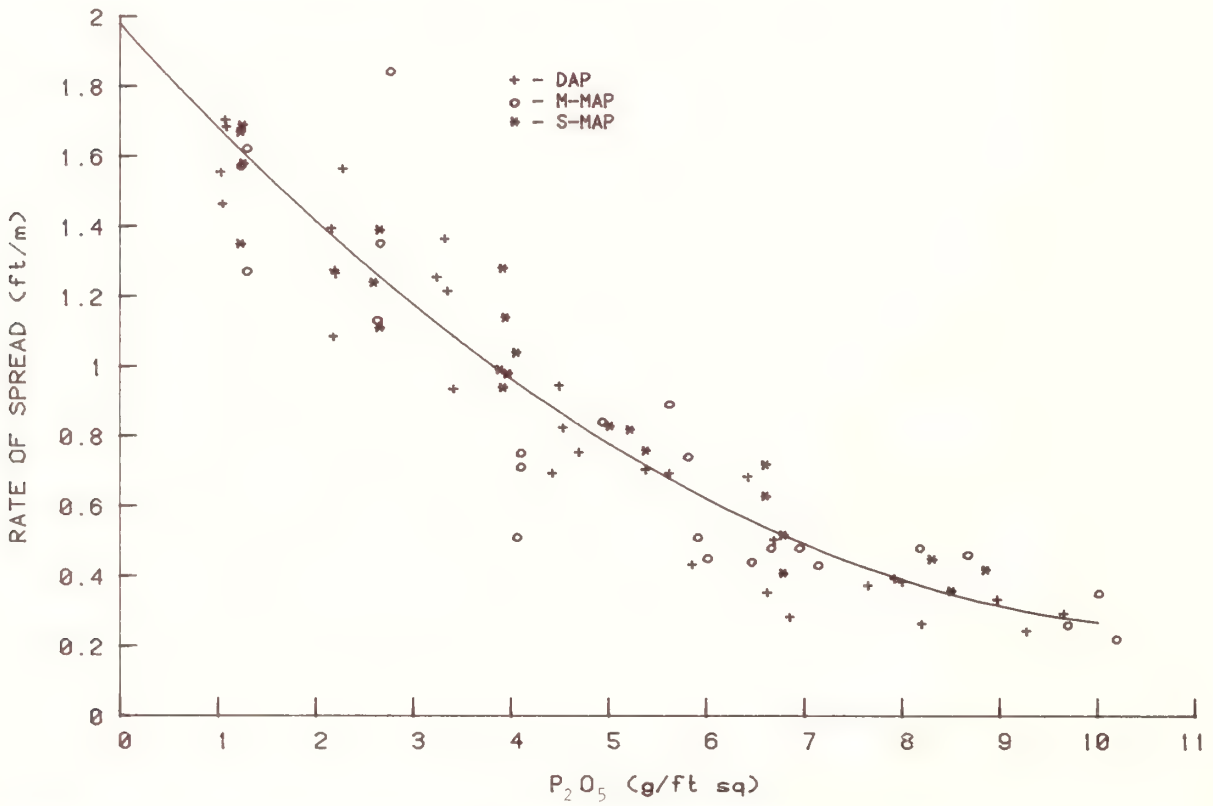

Figure 5.—Effect of DAP, M-MAP, and S-MAP on spread rate of pine needles. (Equation for pooled data is plotted.)

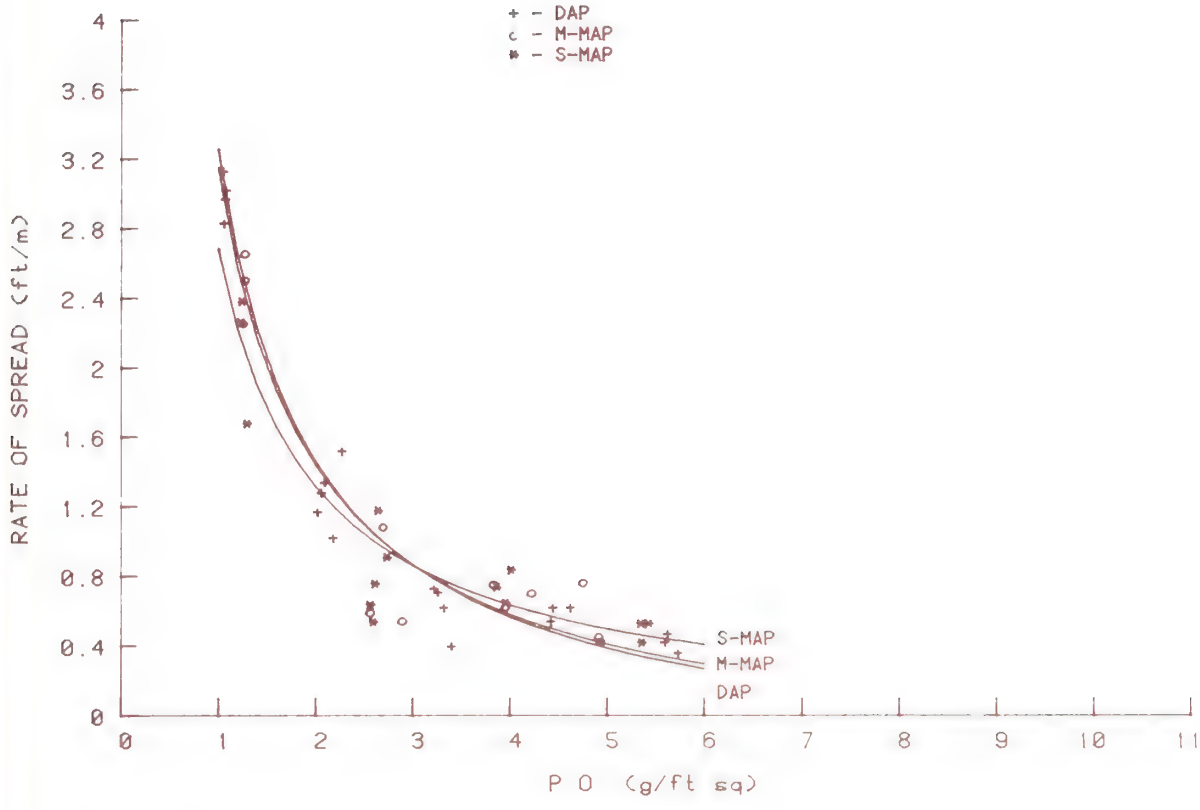

Figure 6.—Effect of DAP, M-MAP, and S-MAP on spread rate of excelsior.

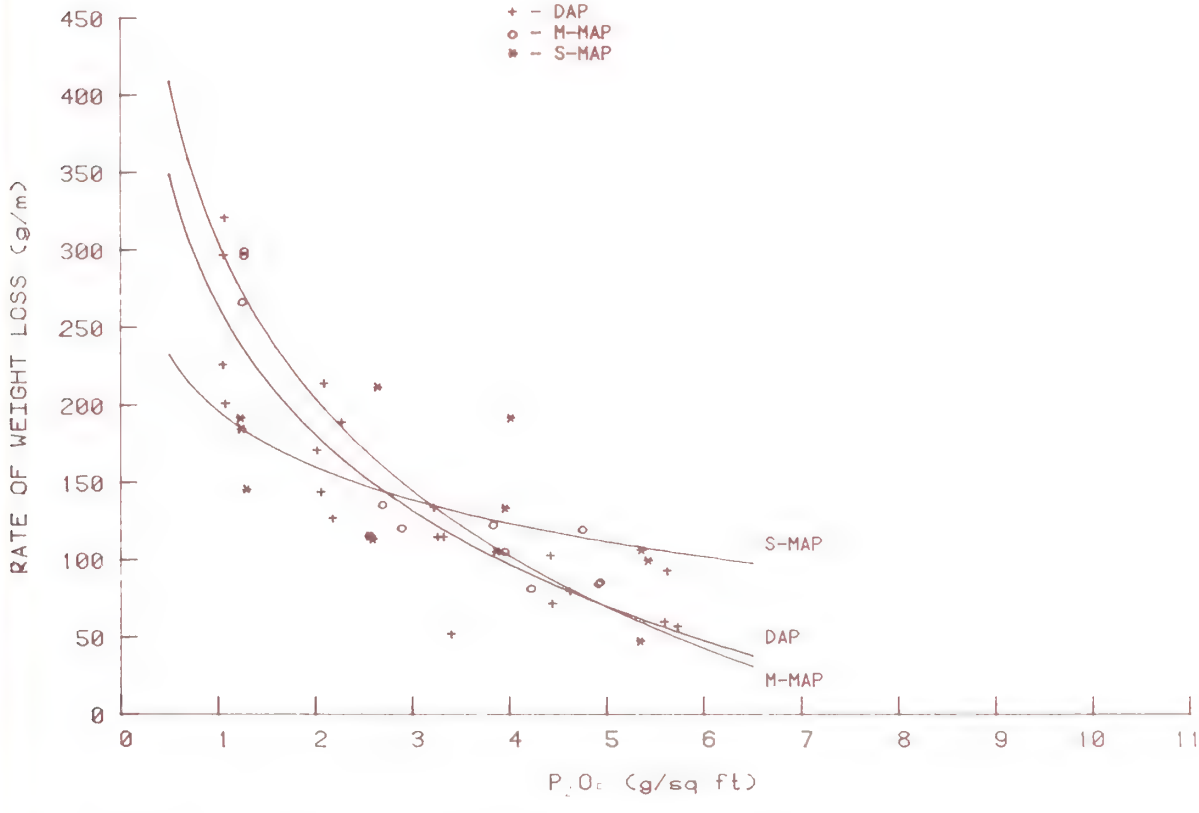

Figure 7.—Effect of DAP, M-MAP, and S-MAP on weight loss rate of excelsior.

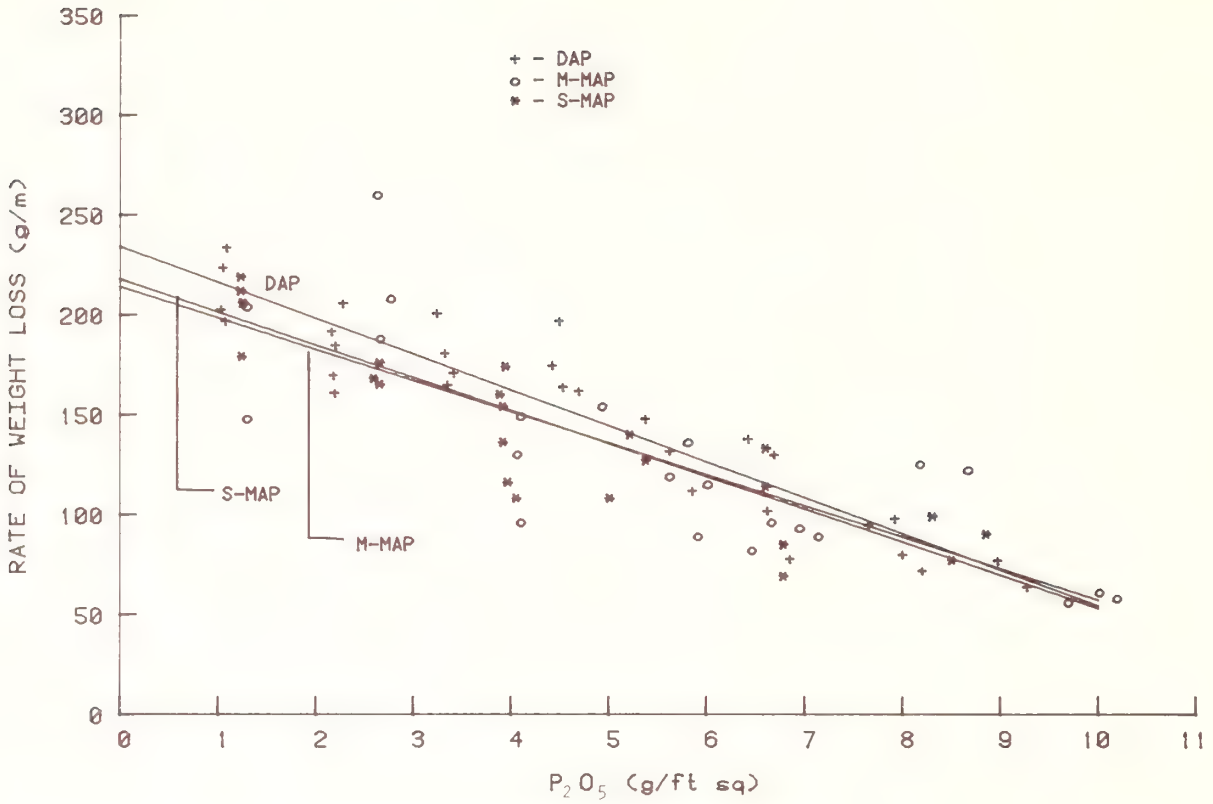

Figure 8.—Effect of DAP, M-MAP, and S-MAP on weight loss rate of pine needles.

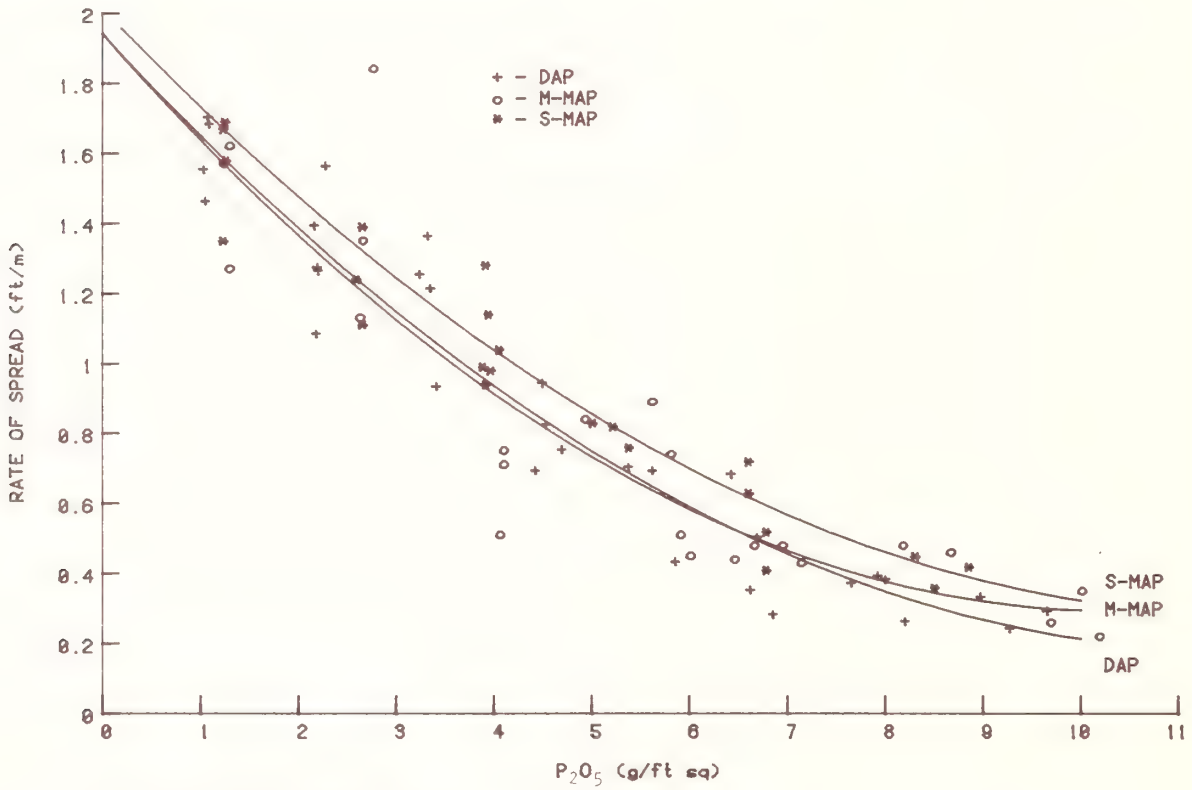

Figure 9.—Effect of DAP, M-MAP, and S-MAP on spread rate of pine needles.

SUMMARY AND DISCUSSION

The study objective was to compare the fire-retarding effectiveness of diammonium phosphate and several samples of monoammonium phosphate. Diammonium phosphate has been the standard for several years; therefore, the other chemicals were compared to its effectiveness. M-MAP and S-MAP proved to be as effective as DAP for retarding flaming and glowing combustion when compared on an equal P_2O_5 equivalent basis under statistical analysis. The other three samples—D-MAP, A-MAP, and T-MAP—(even though fewer burning tests were performed) appear to be equally as effective. The differences in flammability reduction are because of experimental error and are not statistically significant. They are probably caused by inconsistencies and variations in fuel bed construction, fuel physical configuration, fuel moisture content, environmental conditions, and so forth.

These tests and others (George and Susott 1971) indicate that the most important chemical characteristic is the available phosphorus (P). As the chemical is heated, the phosphate (PO_4) compounds are converted to phosphoric acid (H_3PO_4) that alters pyrolysis of the fuel. Both diammonium and monoammonium phosphates are converted easily to H_3PO_4 because the ammonia cations (NH_4) are driven off at low temperature:

$$(NH_4)_2HPO_4 \xrightarrow{166^\circ C} NH_4H_2PO_4 + NH_3\uparrow$$

$$NH_4H_2PO_4 \xrightarrow{190^\circ C} H_3PO_4 + NH_3\uparrow + H_2O + P_2O_5$$

Phosphate anions (PO_4), when combined with sodium (Na), calcium (Ca), potassium (K), and others, cannot be converted to H_3PO_4 readily, and therefore do not make the PO_4 available in the most effective form as fire retardant.

Whether or not one or two ammonias are associated with the P does not appear to make a difference. The method for associating the ammonia with the phosphate (PO_4) also does not appear to affect the fire-retardant ability. Whether ammonia is extracted from coal smoke that is being "scrubbed" with phosphoric acid (D-MAP) or whether the acid is being ammoniated by bubbling ammonia gas into it (S- and T-MAP) seems to make no difference in the availability of P and the resulting fire-retarding effectiveness. A-MAP, produced from a less pure acid, is as effective as the other MAP forms when most of the impurities have been removed after ammoniation. The fire-retarding effectiveness of each MAP (and also DAP), when in a pure form, can be equated on the P or P_2O_5 content. Any formulations containing impurities may change the level of effectiveness.

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The study quantified differences between fire-retarding abilities of monoammonium phosphate samples from five different sources. Ponderosa pine needles and aspen excelsior fuel beds were spray-treated with different levels of chemical solutions, dried, and burned under controlled laboratory conditions. Flame spread and energy release rates were used for comparisons. All five monoammonium phosphate samples proved to be equally effective.

KEYWORDS: forest fire retardent, ammonium phosphate, monoammonium phosphate, flame spread rate, energy release rate, chemical manufacturing method

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Winter Injury of Sagebrush and Other Wildland Shrubs in the Western United States

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RESEARCH SUMMARY

Extensive winter injury of native wildland shrubs occurred in the Western United States during the winter of 1976–77. *Artemisia tridentata* was damaged most extensively followed by *Ceanothus* spp., *Arctostaphylos* spp., *Purshia* spp., and 32 other species of shrubs. The record low precipitation during this period, and consequential low snow cover in areas of normally heavy snow cover, combined with other factors that led to the injury.

Cover Photo—A mountain valley at the headwaters of the Big Lost River on the Challis National Forest in south-central Idaho. Virtually all mountain big sagebrush plants were killed.

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INTRODUCTION

Wildland shrubs are increasingly important on western rangelands (McKell and others 1972; McKell 1975a, 1975b; McArthur and others 1974) in the restoration of disturbed areas (McArthur and others 1974; Monsen 1975) and for use on big-game ranges (Plummer and others 1968). Sagebrush, *Artemisia* spp., alone occurs on more than one-third of the 820 million acres (332 million ha) of western shrublands (Beetle 1960; Plummer 1974). Its importance stems, if not from its ubiquity, from its aggressiveness and tremendous diversity and adaptability (Beetle 1960; McArthur and Plummer 1978).

Weather extremes are a recognized important environmental element in the survival and natural selection of plants. The low precipitation period during the winter of 1976–77 may have been an example of such an extreme. Precipitation during this period was near the lowest in recorded history over most of the West. Following that winter, extensive areas of sagebrush kill were observed in Idaho, Nevada, Utah, western Wyoming, and western Colorado. Severe damage to other shrub species was also observed. Winter injury appeared to be the primary cause. Some plant species appear to have been killed or damaged by drought alone.

The objective of this paper is to briefly review winter injury of plants and shrubs in particular, document the observed winter injury of 1976–77, and correlate the occurrence with weather records.

REVIEW

Winter injury of conifers, hardwood trees, and ornamental shrubs is well documented (for example, Hubert 1918; Hilborn 1937; Nash 1943; Hunter-Blair 1946; Spaulding 1946; Wisconsin Department of Agriculture 1948; Curry and Church 1952; Duffield 1956; Daubenmire 1957; Day and Peace 1946; Powell 1972). However, reference to winter injury of endemic wildland shrubs is relatively rare. Cottam (1937) reported extensive damage to *Covillea tridentata* (*Larrea divaricata* Cav., creosote bush), *Strombocarpa ordata* (*Prosopis pubescens* Benth., mesquite), and *Prosopis glandulosa* (*Prosopis juliflora* [SW.] DC) following a cold period in southwestern Utah. In this instance the damage was probably caused by freezing of plant tissue, and most of the plants apparently recovered (Frosberg 1938). Frost injury of bitterbrush (*Purshia tridentata*) occurred over a large area of eastern California when several unusually cold, below freezing days followed an unusual warm spell in early April that stimulated bud growth (Smith and others 1965). Exposed bitterbrush foliage was damaged in northern Utah apparently from extreme temperatures of -35°F (-37°C) and 37°F (-38°C) in early December and January following relatively warm periods (Jensen and Urness 1979). Fourwing saltbush (*Atriplex canescens*) received winter injury in two off-site performance plantings in central Utah (Van Epps 1975). The injury in this case was attributed primarily to unusually low temperatures; hardiness varied with the point of origin of the 20 accessions. Schumaker and others (1979) and Hanson and others (1982) reported the loss of *Artemisia tridentata* ssp. *vaseyana* (mountain big sagebrush) in an area of southwestern Idaho that occurred during winter 1976–77. Areas of most intense kill were those normally covered by 3.3 ft (1 m) or more of snow. They hypothesized that sagebrush plants remained active during most of the winter and became desiccated due to lack of normal soil moisture. A 50 percent loss of shrub cover and increase in grass and forbs followed the sagebrush kill. Buckbrush (*Ceanothus* sp.) (Stickney 1965) and manzanita (*Arctostaphylos* spp.) commonly incur winter injury throughout the West during winters of incomplete snow cover. Perhaps due to the commonness of this injury and usual recovery little attention is given. Tarry and Shaw (1966) associated *Armillaria mellea*, a root pathogen, with a dieback disease of *Ceanothus* spp. following winter injury in the Pacific Northwest.

Winter injury has a rather broad meaning, and the mechanism is not completely understood (Slatyer 1976). Plants presumably suffer winter injury by freezing due to a lack of sufficient innate cold hardiness or absence of winter dormancy in cold-hardy plants, and due to winter drought or desiccation (Michael 1963, 1967; Tranquillini 1964; Kramer 1969; Mazur 1969; Sakai 1970; Alden and Hermann 1971). Winter injury to nonindigenous or exotic plants adapted to warmer regions can usually be attributed to direct freezing. Plants in their native habitat or exotics may suffer damage from absence of winter dormancy or from desiccation, and the critical periods are usually in early and late winter (Day and Peace 1946; Peace 1962; Parker 1963).

Dormancy is an adaptive phenomenon in plants that enables them to resist and survive moisture and temperature extremes of the external environment where they are indigenous. External environmental factors that initiate dormancy by influencing growth are usually a combination of temperature, moisture, nutrition, light quality, photoperiod, and temperature during light and dark periods (Vegis 1964). The characteristic response

of plant species to these factors in the initiation and length of dormancy is hereditarily controlled. Prior to dormancy or full rest formation in fall or early winter, an unusual cold wave can result in freezing injury to native as well as exotic plants. In late winter after dormancy has ended, an unusual warm spell that stimulates growth activity, followed with a return to winter cold, can result in freezing injury. Leaf and shoot kill of evergreen plants during winter and spring is usually expressed later during the summer as the foliage turns brown (for example, Felt 1943). The other type of winter injury, desiccation, is thought to result from lethal dehydration resulting from continued transpiration with lack of sufficient water absorption from the root system (Kramer 1969). With the absence of snow cover, the soil and root systems may freeze; or with severe cold, lower stems may freeze, preventing replacement of transpirational water loss in upper plant parts (Olberg 1955; Sakai 1970). Rapid temperature fluctuations, drying winds, and bright sunny winter or early spring days are believed to be related to this type of winter injury (White and Weiser 1964; Watanabe 1969).

METHODS

Extensive kill of sagebrush was called to our attention by Walt Mueggler and Ed Schlatterer of the USDA Forest Service, and G. A. Schumaker, USDA Science and Education Administration, Boise, Idaho. They observed areas of recently killed plants in central and southern Idaho during summer 1977. We visited these areas and others in Utah during September 1977 in an attempt to determine the cause. The extensive nature and pattern of damage, not only to sagebrush but also to other shrub species, implicated winter injury as the probable cause. In view of the extraordinarily low precipitation during winter 1976–77 throughout most of the West, it seemed worthwhile to determine the extent of winter injury to sagebrush and other shrub species throughout the West. To accomplish this, it seemed expedient to make a survey of land management units of the Forest Service, Bureau of Land Management, and State Divisions of Wildlife Resources. Because our primary interest was big sagebrush (*Artemisia tridentata*), we limited the survey to the general distributional limits of this species (Little 1976), excluding Washington, Arizona, New Mexico, and southern California (fig. 1). Information requested included (1) shrub species affected, (2) location, (3) elevation, (4) intensity of injury, and (5) symptoms observed.

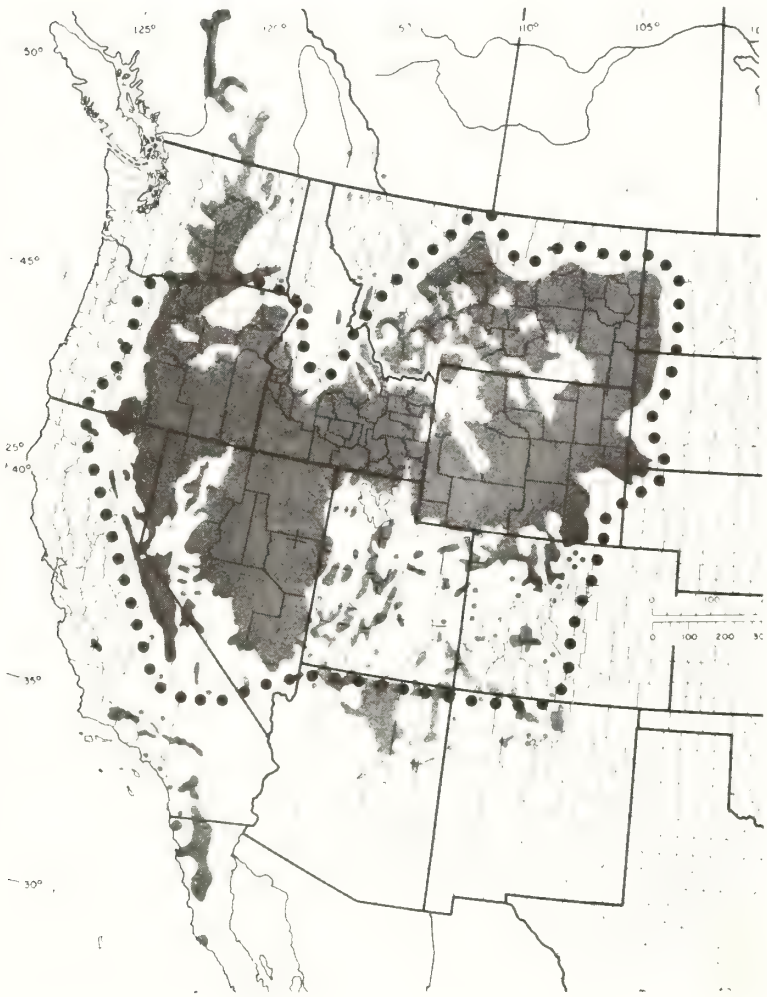

Figure 1.—Distribution of *Artemisia tridentata* in the western United States. Dotted line encircles the general limits of the winter injury survey.

Climatological data for the States falling within the area of interest were obtained from the National Oceanic and Atmospheric Administration, National Climatic Center, Ashville, N.C. Monthly precipitation and temperature records were examined for October through April 1976–77. The monthly actual and percentage of normal climatic divisional average precipitation was computed for each State. Only those divisions that fell within the survey limits were used to obtain the average for each State. The average monthly means and degrees (°Farenheit) temperature departures from normal were computed for each State for the same climatic division as for precipitation. Precipitation and temperature normals were based on the 1941–70 record. Precipitation in areas of little or no reported winter injury was compared with that of those where the most extensive injury was reported. This was done by matching management areas with climatic divisions and selecting those that corresponded most closely. Other factors considered were elevation (that is, mountains, valleys, plateaus) and distribution of shrubs, particularly big sagebrush.

RESULTS

Description of Winter Injury

In the areas of sagebrush injury we visited in south-central and southern Idaho and northern Utah, damage occurred primarily above 6,000 ft (1 800 m). This was generally true with survey reports, although in California and Oregon the elevation was somewhat lower. Typically the most severe damage occurred in mountain valleys (cover photo) and other areas of normally deep snow cover (fig. 2). Southwesterly exposures and windswept ridges were usually free of injury. Virtually all large plants of mountain big sagebrush were killed on the high plateau areas we surveyed on Idaho's Sawtooth National Forest and Utah's Uinta and Manti-LaSal National Forests (fig. 3).

Figure 2.—A depressed area on the lee of a glacial morain with winter-killed mountain big sagebrush. North of Borah Peak, Lost River Range in Idaho.

Figure 3.—Extensive sagebrush winter-kill on the high Cassia Plateau of southern Idaho, Sawtooth National Forest.

Even in the most severe kill areas, however, some young plants up to 12 inches (30 cm) high were not affected (fig. 4). Partial kill of large plants was common (fig. 5), with increased frequency bordering normally exposed areas, protected areas, and areas ascending from valley or canyon bottoms. It was typical for mountain big sagebrush to be killed in canyon bottoms, but not injured at all on adjacent normally exposed or partially exposed slopes. Of the areas we visited, mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*) was the only big sagebrush observed to be injured. Basin or valley big sagebrush (*Artemisia tridentata* ssp. *tridentata*) occurs at lower elevations and apparently was not damaged as extensively. This appeared to be generally true from survey reports although familiarity with the subspecies is not universal enough to make this generalization. *Juniperus communis*, a procumbent shrub (fig. 6), was injured virtually everywhere it occurred over the southeastern portion of the Challis National Forest. The foliage on the entire to upper portions of plants had turned brown, but it did not appear that the plants were entirely killed. On the Targhee National Forest in southeastern Idaho, huckleberry (*Vaccinium* spp.), which grows under a canopy of lodgepole pine, was damaged over large areas. Characteristically the upper 6 to 12 inches (15 to 30 cm) of plants were dead and leafless. Snowberry (*Symphoricarpos* spp.) damage on the southern Sawtooth National Forest (fig. 7) in Idaho was similar to that of *Vaccinium*. Spotty to intense winter injury of *Ceanothus* sp. was present almost everywhere the plant occurred (fig. 8).

Figure 4.—Meadow with winter-killed sagebrush. Note patch of unaffected young sagebrush plants in center of photo, east of Oakley, Idaho, Sawtooth National Forest.

Figure 5.—A partially killed mountain big sagebrush on the Sawtooth National Forest, south of Albion, Idaho.

Figure 6.—Common juniper (arrow), a procumbent shrub, received extensive damage on the Challis National Forest of Idaho.

Figure 7.—Winter-killed snowberry plants on the Sawtooth National Forest, south of Albion, Idaho.

Figure 8.—Typical spotty winter injury of *Ceanothus* near Mt. Harrison, Sawtooth National Forest, Idaho.

Results of the survey of Federal and State land management units are given in tables 1, 2, and 3; and the shrub species damaged are summarized in table 4. Within the survey area, which corresponds generally to the distributional range of big sagebrush, there were large areas with no reported winter injury. These were primarily almost all of Montana and the eastern two-thirds of Wyoming and Colorado. The areas with the most severe winter injury were most of southern Idaho; southwestern Wyoming; northwestern Colorado; northeastern Utah, Nevada, and California; and south-central Oregon. (Refer to tables 1 through 3 for more specific locations.) At least 36 species in 21 genera were reported damaged. *Artemisia tridentata* injury was reported to occur in 190 localities throughout the survey area, followed by *Ceanothus* (118), *Arctostaphylos* (49), and *Purshia* (33). Based on the survey estimate, almost entire kill of sagebrush occurred in locations totaling 340,000 acres (138 000 ha), with spotty kill in 80 additional locations. The actual area of winter kill was undoubtedly much greater. Injury to other species occurred in a much lesser number of locations (table 4). This is probably a reflection of the relative abundance of the various species at least for those at elevations higher than 6,000 ft (1 800 m). We suspect that the lower elevation desert shrubs, *Atriplex, Ceratoides, Grayia, Sarcobatus*, and especially *Coleogyne* were probably killed or injured by drought alone.

Table 1.—Winter injury of western wildland shrubs on National Forest lands

Shrub species	No. of locations[1] of winter injury	Approximate elevation (1,000 ft)	Intensity of injury[2]	Symptoms[3]
CALIFORNIA				
Eldorado				
Arctostaphylos spp.	3	5.2	1	1-2
Ceanothus leucodermis	1	2.0-3.0	2	1
Ceanothus integerrimus	3	3.2-6.0	1-2	2-4
Inyo				
Arctostaphylos spp.	1	7.0-8.5	2	2-4
Ceanothus velutinus	1	7.0-8.5	2	1-3
Modoc				
Arctostaphylos patula	4	4.6-7.0	2-3	1-2
Artemisia tridentata	1	5.0	2	1-3
Ceanothus velutinus	1	4.5	2-3	2-3
Cercocarpus ledifolius	1	5.0	3	1-2
Juniperus occidentalis	1	--	3	1,3
Purshia tridentata	1	4.2-4.8	1-2	2
Plumas				
Arctostaphylos spp.	1	5.0	2	1,3
Artemisia tridentata	1	5.0	2	2
Ceanothus cordulatus	1	5.0	2	1,3
Ceanothus cuneatus	1	5.0	2	1,3
Ceanothus velutinus	1	5.0	2	2,3
Stanislaus				
Ceanothus cordulatus	1	6.0	2	2,3
Tahoe				
Arctostaphylos patula	3	5.0-7.0	2	2-3
Ceanothus cordulatus	1	6.0-7.0	2	1-3
Ceanothus velutinus	1	4.0-5.5	2	2-3
Prunus emarginata	1	6.9	2	2
COLORADO				
Arapaho-Roosevelt				
None reported				
Gunnison-Grand Mesa Uncomphagre				
Artemisia tridentata	1	9.4	1	2,4
Purshia tridentata	1	9.0	1	2,3
Rio Grande				
None reported				
Routt				
Ceanothus spp.	8	6.8-11.0	1-3	2,3
Juniperus spp.	2	8.2-11.0	2	1,3
Quercus spp.	1	6.8-7.0	2-3	2-3
San Juan				
None reported				
White River				
Quercus gambelii	1	7.5	2	2
Symphoricarpos oreophilus	1	7.5	2	2

(con.)

Table 1.—(con.)

Shrub species	No. of locations[1] of winter injury	Approximate elevation (1,000 ft)	Intensity of injury[2]	Symptoms
IDAHO				
Boise				
Artemisia tridentata	7	5.0-8.0	2	1
Ceanothus sanguineus	1	8.0	3	2
Ceanothus velutinus	5	6.2-7.4	1-2	3
Ceanothus spp.	1	3.0-6.0	2	3
Caribou				
Artemisia tridentata	4	6.6-8.0	1-2	1-2
Ceanothus velutinus	2	5.8-8.0	1-2	1,3
Ceanothus spp.	1	--	2	2,3
Challis				
Arctostaphylos spp.	2	7.0-8.0	1-2	1-3
Artemisia tridentata	24	6.0-7.8	1-2	1-2
Ceanothus sanguineus	1	3.8-8.0	1	2,3
Ceanothus spp.	1	6.0	1	1,3
Juniperus communis	1	7.0	1	1-3
Purshia tridentata	2	6.0-6.5	1-2	1
Vaccinium spp.	1	8.0	2	2-3
Salmon				
Artemisia tridentata	15	6.3-8.5	1-2	1-2
Ceanothus velutinus	4	5.8-6.6	2	2,3
Sawtooth				
Artemisia tridentata	12	5.5-8.0	1-3	1,2
Ceanothus spp.	2	5.5-8.0	1-2	2,3
Purshia tridentata	1	6.6	2	1
Symphoricarpos spp	1	6.5	2	2
Targhee				
Artemisia tridentata	3	6.5-7.0	2	1
Ceanothus spp.	5	5.0-7.4	2-3	1-2,3
Vaccinium spp.	1	5.0-6.0	2	2,4
MONTANA				
Beaverhead				
Artemisia tridentata	2	6.9-7.8	1-2	1-2
Custer				
None reported				
Deerlodge				
None reported				
Gallatin				
Ceanothus velutinus	1	--	2	2-3
Lewis and Clark				
None reported				
NEVADA				
Humboldt				
Amelanchier spp.	1	6.0-8.0	2	1-2
Artemisia tridentata	7	8.0-8.4	2	1,2
Ceanothus spp.	1	6.0-8.0	2	1-2
Cercocarpus spp.	4	6.0-8.0	1	1-2
Purshia tridentata	4	6.0-8.0	1	1-2
Symphoricarpos spp.	4	6.0-8.0	1	1-2
Toiyabe				
Artemisia tridentata	9	7.0-9.5	1-2	1-2
Ceanothus velutinus	1	6.5-10.0	1	2
Ceanothus spp.	1	--	1	1-3

(con.)

Table 1.—(con.)

Shrub species	No. of locations[1] of winter injury	Approximate elevation (1,000 ft)	Intensity of injury[2]	Symptoms[3]
OREGON				
Deschutes				
Arctostaphylos patula	5	5.0–7.0	2–3	1–4
Ceanothus velutinus	2	6.0–7.5	2–3	1–4
Chrysothamnus nauseosus	1	4.5	2?	2
Purshia tridentata	1	4.7	1	1
Fremont				
Arctostaphylos spp.	4	4.5–5.5	1	1–4
Artemisia tridentata	2	5.0–5.5	1	1–2
Ceanothus prostratus	1	5.5	1	1–3
Ceanothus velutinus	3	5.0–7.0	1–2	1–4
Purshia tridentata	1	4.7	1	1–2
Malheur				
Ceanothus sanguineus	4	5.5–6.5	2	1–2
Ceanothus velutinus	1	5.0	2	2
Salix spp.	1	5.2	2	2
Ochoco				
Ceanothus velutinus	1	4.0–6.5	2	3
Umatilla				
None reported				
Wallowa-Whitman				
Ceanothus spp.	1	5.0–9.0	1	2
Winema				
Arctostaphylos spp.	7	4.4–8.0	1	1
Ceanothus velutinus	7	4.4–8.0	1	1–2
Purshia tridentata	2	4.2–7.0	1	1–2
UTAH				
Ashley				
Arctostaphylos patula	2	7.4–8.4	1	2–3
Artemisia tridentata	3	7.0–9.0	1–2	1–2
Cercocarpus montanus	2	6.0–8.2	1–2	1
Purshia tridentata	1	7.0–8.2	1–2	1
Dixie				
Arctostaphylos spp.	3	6.9–9.0	2	1
Artemisia spp.	2	7.0–9.0	2	1
Purshia tridentata	3	8.5–9.5	1–2	1–2
Fishlake				
Amelanchier spp.	1	7.5	1	1
Arctostaphylos spp.	6	8.5	2	1,3
Artemisia tridentata	1	7.5–9.1	1	2
Purshia tridentata	2	7.5–9.1	1–2	1–3
Manti-LaSal				
Arctostaphylos spp.	1	7.0–8.0	2	1–2
Artemisia tridentata	6	7.0–10.0	1–2	1–2
Artemisia spp.	1	9.0–10.0	1–2	1–2
Ceanothus spp.	3	7.5	2	3
Juniperus spp.	1	8.0–9.0	3	3
Uinta				
Artemisia cana	1	6.0–8.0	2	1
Artemisia tridentata	2	6.0–8.0	1–2	1–2
Ceanothus spp.	3	7.0–9.0	1	2
Chrysothamnus spp.	1	6.0	1	2
Juniperus osteosperma	2	6.5	2	3–4
Pachistima spp.	3	7.0–9.0	2	2
Quercus gambelii	3	7.0–9.0	1	2
Wasatch-Cache				
Artemisia tridentata	3	6.5–9.0	1–3	2–4
Ceanothus spp.	3	6.6–9.0	2	1,4
WYOMING				
Bighorn				
Juniperus communis	1	7.0–9.0	2	3
Bridger-Teton				
Artemisia tridentata	6	6.0–9.0	1–3	1–2
Ceanothus velutinus	2	6.5	2	2–3
Salix spp.	1	7.2–10.0	2	1–2
Medicine Bow				
None reported				
Shoshone				
Artemisia tridentata	2	8.0	1	1–2

[1]Locations represent separate areas of shrub winter injury that varied in size from less than an acre to thousands of acres.
[2](1) Areas of from a few to thousands of acres where virtually all plants suffered winter injury, (2) areas of from a few to thousands of acres where winter injury occurred in scattered patches, (3) areas usually small in size where a few plants received winter injury.
[3](1) Entire kill, (2) partial kill, (3) reddish-brown foliage, (4) dead leafless shoots.

Table 2.—Winter injury of western wildland shrubs on Bureau of Land Management lands

Shrub species	No. of locations[1] of winter injury	Approximate elevation (1,000 ft)	Intensity of injury[2]	Symptoms
CALIFORNIA				
Bishop				
None reported				
Folsom				
None reported				
Redding				
None reported				
Riverside				
None reported				
Susanville				
Artemisia tridentata	1	5.8	3	1
Juniperus occidentalis	1	5.2	2	
COLORADO				
Cannon City				
None reported				
Craig				
Amelanchier alnifolia	1	7.0-8.0	2	2
Artemisia spinescens	1	6.0	2	2-4
Artemisia tridentata	3	6.6	2-3	2
Atriplex confertifolia	1	6.0	2	1-4
Atriplex gardneri	1	6.0	2	1-3
Ceratoides lanata	1	6.0	2	2
Cercocarpus montanus	1	7.3	3	2-4
Juniperus spp.	1	6.2-6.9	3	3
Pinus edulis	1	6.2-6.9	3	3
Purshia tridentata	1	7.2	2	4
Sarcobatus vermiculatus	1	6.0	2	4
Grand Junction				
Arctostaphylos patula	1	7.7	3	3
Artemisia tridentata	5	6.0-8.5	1-2	1-2
Quercus gambelii	1	7.5	2	4
Montrose				
Artemisia tridentata	1	6.0-10.0	2	1,2
Juniperus communis	2	9.0-11.0	2	2-3
Purshia tridentata	1	6.5	2	1-2
Salix anglorum	3	7.2	2	2,4
IDAHO				
Boise				
Artemisia tridentata	3	5.8-7.0	1-2	1-2,4
Cenothus velutinus	3	5.0-7.0	1-2	2-3
Juniperus spp.	1	5.8	2	2
Burley				
Amelanchier alnifolia	1	5.8	1	1
Artemisia tridentata	3	5.8-6.2	1-2	1-2
Ceanothus spp	2	6.3-6.4	2	3
Chrysothamnus nauseosus	2	5.8-6.2	1	1-2
Purshia tridentata	1	5.8-6.2	1	1-2
Idaho Falls				
Artemisia tridentata	3	4.8-7.5	1-2	1-4
Ceanothus velutinus	4	6.0-7.0	1-3	1,3
Salmon				
Artemisia tridentata	17	6.5-8.8	1-3	1-2,4
Ceanothus velutinus	2	6.0-7.5	2	2
Purshia tridentata	1	6.5	2	1-2
Shoshone				
Artemisia tridentata	1	5.8	2	2
Ceanothus velutinus	2	5.8-6.8	2	2
Prunus virginiana	2	5.8-6.8	2	2
MONTANA				
Butte				
Ceanothus velutinus	5	5.0-5.4	2	3
Lewistown				
None reported				
Miles City				
None reported				

(con.)

Table 2.—(con.)

Shrub species	No. of locations[1] of winter injury	Approximate elevation (1,000 ft)	Intensity of injury[2]	Symptoms[3]
NEVADA				
Battle Mountain				
None reported				
Carson City				
Arctostaphylos spp.	1	6.0	1	2
Elko				
Artemisia tridentata	3	6.0–7.5	1–2	1
Ceanothus spp.	1	6.5–7.0	1	3
Purshia tridentata	4	6.0–7.5	1–2	1–4
Ely				
Arctostaphylos spp.	2	8.0–9.0	2	2
Artemisia tridentata	1	8.0–8.8	2	2
Las Vegas				
None reported				
Winnemucca				
Ceanothus velutinus	2	6.5–7.8	2	4
OREGON				
Baker				
None reported				
Burns				
Sarcobatus vermiculatus	1	4.0–4.2	1	2
Lakeview				
Artemisia tridentata	1	4.6	2	1–2
Juniperus occidentalis	1	4.5	2	2–3
Prineville				
None reported				
Vale				
Purshia tridentata	1	5.6	1	2,3
OREGON-WASHINGTON				
Spokane				
None reported				
UTAH				
Cedar City				
Coleogyne ramosissima	1	3.0	1	2,4
Moab				
None reported				
Richfield				
Artemisia tridentata	4	5.4–8.5	2	2
Coleogyne ramosissima	1	4.4–5.2	1	2,4
Ephedra spp.	1	4.4–5.6	1	1–4
Juniperus osteosperma	4	5.0–7.0	2	1–3
Salt Lake				
Artemisia tridentata	2	4.6–6.6	2	1–2
Ceanothus velutinus	1	7.2	2	2–3
Juniperus osteosperma	1	4.6	2	1
Vernal				
Artemisia nova	5	5.0–6.0	1–2	1–2
Artemisia tridentata	8	5.0–6.0	1–2	1–2,4
Atriplex confertifolia	5	5.0–6.0	2	2,4
Juniperus osteosperma	3	5.6–6.5	1	1–3
WYOMING				
Casper				
None reported				
Rawlins				
None reported				
Rock Springs				
Arctostaphylos spp.	2	7.0–8.0	1	2–3
Artemisia cana	1	6.5–7.0	2	2,4
Artemisia tridentata	4	6.0–8.0	1–2	1–2
Atriplex confertifolia	1	6.1	1	1
Ceanothus spp.	1	7.5–8.5	1	2
Chrysothamnus spp.	1	6.1	1	1
Grayia spinosa	1	6.1	1	1
Sarcobatus vermiculatus	1	6.1	1	1
Worland				
Atriplex nuttallii	1	4.5	2	2
NORTH DAKOTA				
Dickinson Wyo.				
None reported				

[1]Locations represent separate areas of shrub winter injury that varied in size from less than an acre to thousands of acres.

[2](1) Areas of from a few to thousands of acres where virtually all plants suffered winter injury, (2) areas of from a few to thousands of acres where winter injury occurred in scattered patches, (3) areas usually small in size where a few plants received winter injury.

Table 3.—Winter injury of western wildland shrubs reported by State Divisions of Wildlife Resources

Shrub species	No. of locations[1] of winter injury	Approximate elevation (1,000 ft)	Intensity of injury[2]	Symptoms[3]
COLORADO				
Southwest				
Artemisia tridentata	1	8.5	2	3
Purshia tridentata	1	8.0	2	3
Northwest				
None reported				
IDAHO				
Region 1				
Ceanothus spp.	1	5.0	1	1
Region 2				
None reported				
Region 3				
Artemisia tridentata	2	5.6	1	1
Ceanothus spp.	4	4.0-6.0	1	1-3
Region 4				
Artemisia tridentata	4	5.0-7.0	1	1
Region 6				
Artemisia tridentata	4	6.0-8.0	1	1-2
Ceanothus spp.	2	6.0-7.0	1	2-3
NEVADA				
Region II				
Artemisia tridentata	2	6.5-7.0	1-2	1-2
Ceanothus spp.	1	6.8-8.0	2	3
Purshia tridentata	5	6.5-8.0	1-2	1-2,4
OREGON				
Southeast Region				
Ceanothus prostratus	4	5.0	2	1-4
Symphoricarpos spp.	4	5.0	2	1-4
UTAH				
Southern Region				
Artemisia tridentata	3	5.0	1	1
Pinus edulis	1	5.0	3	1
Southeastern Region				
Artemisia tridentata	2	5.0	1	1-2
Northern Regions				
Ceanothus velutinus	6	6.0-9.0	2	2,3
WYOMING				
Southwest				
Artemisia cana	1	6.0-9.0	1	1-2
Artemisia tridentata	3	6.5-9.0	1	1-2
Ceanothus velutinus	3	7.0-8.5	1	2-3
Juniperus communis	2	8.0-9.0	2	3
Vaccinium spp.	2	8.0-9.0	1-2	1-3
Southeast				
None reported				

[1]Locations represent separate areas of shrub winter injury that varied in size from less than an acre to thousands of acres

[2](1) Areas of from a few to thousands of acres where virtually all plants suffered winter injury, (2) areas of from a few to thousands of acres where winter injury occurred in scattered patches, (3) areas usually small in size where a few plants received winter injury

[3](1) Entire kill, (2) partial kill, (3) reddish-brown foliage, (4) dead leafless shoots

Table 4.—List of shrub species reported with winter injury or drought damage

Shrub species	No. of locations observed	Shrub species	No. of locations observed
Amelanchier alnifolia (Nutt.) Nutt.	2	*Coleogyne ramosissima* Torr.	2
Amelanchier Medic. spp.	2		
Arctostaphylos patula Greene	17	Ephedra L. sp.	1
Arctostaphylos Adans. spp.	32		
		Grayia spinosa (Hook.) Moq.	1
Artemisia cana Pursh	3		
Artemisia nova (A. Nels.) Ward	5	*Juniperus communis* L.	6
Artemisia spinescens D.C. Eaton	1	*Juniperus occidentalis* Hook.	3
Artemisia tridentata Nutt.	190	*Juniperus osteosperma* Torr. Little	11
Artemisia L. spp.	4	*Juniperus* L. spp.	5
Atriplex confertifolia (Torr. & Frem.) S. Wats.	7	*Pachistima* Raf. sp.	3
Atriplex gardneri (Moq.) D. Dietr.	1	*Pinus edulis* Engelm.	2
Atriplex nuttallii S. Wats.	1	*Prunus emarginata* (Dougl.) Walp.	1
Ceanothus cordulatus Kellogg	3	*Prunus virginiana* L.	2
Ceanothus cuneatus (Hook.) Nutt.	1		
Ceanothus integerrimus Hook. & Arn.	3	*Purshia tridentata* (Pursh) DC	33
Ceanothus leucodermis Greene	1	*Quercus gambelii* Nutt.	5
Ceanothus prostratus Benth.	5	*Quercus* L. spp.	1
Ceanothus sanguineus Pursh	6		
Ceanothus velutinus Dougl.	55	*Salix anglorum* Schenid.	1
Ceanothus L. spp.	44	*Salix* L. spp.	2
Ceratoides lanata (Pursh) J. T. Howell	1	*Sarcobatus vermiculatus* (Hook.) Torr.	3
Cercocarpus ledifolius Nutt.	1	*Symphoricarpos oreophilus* A. Gray	1
Cercocarpus montanus Raf.	3		
Cercocarpus HBK. spp.	1	*Symphoricarpos* Duhamel. spp.	9
Chrysothamnus nauseosus (Pall.) Britton	3	*Vaccinium* L. spp.	4
Chrysothamnus Nutt. spp.	2		

Correlation with Weather Records

Of the eight Western States included in the study, Oregon, Idaho, California, and Utah had the lowest monthly accumulated percentage of normal precipitation (table 5). Montana and Wyoming were the highest, with Nevada and Colorado intermediate. This agrees roughly with the reported extent of winter injured shrubs. December had the lowest monthly accumulated percentage of normal, with January, November, and February slightly higher. Normally, these are months of higher precipitation and snow cover. A comparison of precipitation in climatic divisions corresponding to areas of high winter injury and low winter injury indicates that the average divisional precipitation was from about 20 to 45 percent lower in areas of high winter injury (tables 6 and 7 and fig. 9). The largest percentage difference was during December through April. The average actual monthly accumulated precipitation was nearly the same in the respective areas.

Table 5.—Monthly accumulated precipitation for October through April, 1976–77[1]

State	Precipitation[2] Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
California	0.45	1.11	1.47	3.12	4.35	5.58	5.75
	53	33	23	34	34	36	34
Colorado	0.56	0.81	0.96	1.25	1.82	2.46	3.93
	48	43	37	41	44	47	60
Idaho	0.56	0.74	0.93	1.53	1.91	1.78	2.92
	62	32	23	29	29	35	33
Montana	0.60	1.01	1.31	2.07	2.33	3.35	3.68
	70	68	65	81	76	86	72
Nevada	0.79	0.96	0.99	1.55	1.87	2.34	2.51
	135	70	45	50	46	49	44
Oregon	0.80	1.58	2.22	3.07	4.34	6.89	7.44
	29	24	19	22	25	32	31
Utah	0.76	0.83	0.87	0.98	1.82	2.52	2.80
	70	42	28	34	35	38	37
Wyoming	0.66	1.04	1.29	1.89	2.21	3.41	4.43
	73	66	59	67	65	78	75

[1]Average precipitation of the climatic divisions within the distributional zone of *Artemisia tridentata*.

[2]Upper figure represents the actual precipitation in inches. Lower figure represents the percent of normal based on the 1941–70 record.

Table 6.—Areas of most intense shrub winter injury and average precipitation of corresponding climatic divisions

Area	Climatic division	Percent monthly precipitation[1]						
		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
CALIFORNIA								
Eldorado N.F. Tahoe N.F. Plumas N.F.	Sacramento drainage	14	22	15	22	26	29	28
Modoc N.F. Susanville (BLM)	Northeast interior basin	40	23	13	20	28	30	29
COLORADO								
Routt N.F. Craig (BLM) Grand Jct. (BLM) Montrose (BLM)	Colorado drainage	23	23	19	28	31	34	39
IDAHO								
Salmon N.F. Challis N.F. Salmon (BLM)	Northeast valleys	34	26	21	30	26	37	34
Boise N.F.	Central mountains	29	24	23	24	25	34	32
Boise (BLM)	Southwest valleys	28	16	13	20	22	28	27
Boise (BLM)	Southwest highlands	84	49	31	28	31	31	32
South Sawtooth N.F. Caribou N.F. Burley (BLM)	Eastern highlands	72	34	27	35	35	39	38
Shoshone (BLM)	Central plains	81	32	19	23	25	27	25
NEVADA								
Humboldt N.F. Elko (BLM)	Northeastern	103	57	35	40	39	45	42
Toiyabe N.F	South-central	248	126	81	79	63	63	55
OREGON								
Fremont N.F. Winema N.F. Lakeview (BLM)	High plateau	31	18	13	14	18	24	24
Winema N.F. Lakeview (BLM) Malheur N.F. Ochoco N.F. Deschutes N.F. Prineville (BLM)	South-central	26	21	15	20	23	25	24
WYOMING								
Bridger N.F. Teton N.F	Snake drainage	49	39	32	39	35	40	38
Rock Springs (BLM)	Green and Bear drainage	14	11	11	16	18	30	31
UTAH								
Uinta N.F. Ashley N.F.	Northern mountains	36	18	12	17	28	35	33
Vernal (BLM)	Uinta Basin	16	10	7	18	26	28	36
Fishlake N.F. North Manti-Lasal N.F. Richfield (BLM)	South-central	71	51	34	38	36	41	36

[1]Average percent of accumulated normal based on 1941-70

Table 7.—Areas of little or no reported winter injury and precipitation of corresponding climatic divisions

Area	Climatic division	Percent monthly precipitation[1]						
		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
COLORADO								
Arapaho N.F. Roosevelt N.F.	Platte drainage	83	62	59	53	54	65	89
Rio Grande N.F.	Rio Grande drainage	39	45	33	41	47	42	52
MONTANA								
Custer N.F.	Southeastern	107	94	87	108	100	121	92
Gallatin N.F.	South-central	108	90	77	90	82	97	80
Deer Lodge N.F. Lewis and Clark N.F.	Central	51	67	60	73	77	81	70
OREGON								
Umatilla N.F. Wallowa-Whitman N.F.	North-central	25	24	21	20	24	30	28
Baker (BLM)	Northeast	30	28	23	25	28	36	35
WYOMING								
Bighorn N.F.	Bighorn	113	83	73	81	78	70	71
Worland (BLM)	Powder Little Missouri, and Tongue drainage	132	116	100	111	115	131	110
Casper (BLM)	Belle Fourche drainage	71	104	93	112	114	130	107
	Cheyenne and Niobrara drainage	68	94	86	92	81	100	103
Medicine Bow N.F.	Upper Platte drainage	57	40	40	47	48	65	74
Rawlins (BLM)	Lower Platte drainage	64	56	51	55	52	64	84
	Wind River	97	70	63	68	67	104	93

[1]Average percent of accumulated normal based on 1941–70 normal.

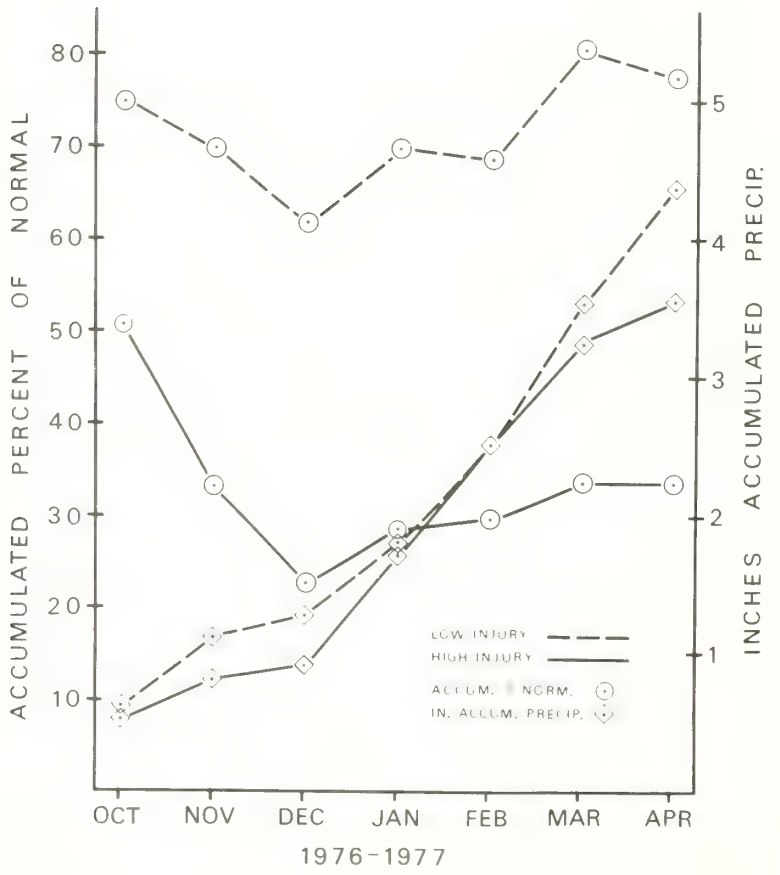

Figure 9.—Comparison of precipitation in areas of low and high amounts of winter injury.

Table 8.—Monthly temperature data for October through April, 1976-77[1]

State	Monthly mean temperature[2]						
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
	°F						
California	59.1	50.9	41.3	37.5	38.6	43.8	56.6
	0.5	0.5	0.3	−1.9	−4.5	−2.9	3.4
Colorado	42.0	32.3	23.4	18.9	28.2	30.9	44.1
	−4.1	−0.7	−0.9	−2.7	0.2	−0.5	2.2
Idaho	45.4	36.4	26.3	19.1	30.0	33.3	48.4
	−1.9	1.8	0.3	−3.5	1.8	−0.6	4.4
Montana	43.6	31.6	26.2	13.5	32.3	32.9	47.4
	2.4	0	3.8	−3.7	9.5	4.1	5.2
Nevada	48.9	41.2	30.6	27.3	36.6	34.0	49.2
	−1.4	2.8	−0.3	−1.5	2.9	−3.3	3.1
Oregon	48.7	41.0	31.7	25.5	37.0	37.0	48.7
	0.3	2.9	−0.3	−3.5	1.3	−1.3	3.6
Utah	49.0	39.7	29.0	25.8	34.5	36.1	52.2
	−2.7	1.5	−0.1	−0.3	2.8	−2.2	3.3
Wyoming	42.0	31.4	24.2	16.1	28.1	29.5	44.7
	0.8	0	1.3	−3.5	4.1	0.4	1.5

[1]Average mean temperature of the climatic divisions within the distributional zone of *Artemisia tridentata*
[2]Upper figure represents the actual monthly mean temperature, °F. Lower figure represents the departure from normal based on the 1941-70 record

The monthly mean temperature departure from normal varied little between States (table 8). For most States, October was below normal, November above, December and January below, February above, March below, and April above.

DISCUSSION AND CONCLUSIONS

As far as we have been able to determine, the winter injury of wildland shrubs reported here is the most extensive winter injury of indigenous plants ever recorded in the United States. The extensive kill of big sagebrush over large areas represents a significant natural vegetational change. These areas will eventually return to sagebrush, however, because some young plants survived and seeding will occur from plants in surrounding areas. Although *Ceanothus* and *Arctostaphylos* commonly receive winter injury, it is seldom reported. This is the first report of winter injury to most of the other shrub species listed here.

It is beyond our objective to establish the precise cause of the reported winter injury by an analysis of past weather records. Averaged weather data tend to mask extremes that likely affect plant development and cause injury most directly. Because of the high elevation, distributional pattern of the various shrubs, and remoteness of the sites involved, few weather stations exist that keep complete long-term records for the precise areas where winter injury occurred.

The weather conditions during the winter of 1976–77 caused winter injury that could have resulted from either freezing or winter desiccation or both. The extremely low precipitation during November through February and resulting low snow cover very likely resulted in frozen soil in those areas where it is normally frozen slightly or not at all. In addition, soil moisture levels were unusually low. The lack of snow and generally above normal temperatures in November could have delayed dormancy formation in shrubs. This, followed by continued lack of snow cover and generally below normal temperatures in December, could have resulted in freezing injury. February was above normal in temperature, which could have stimulated [illegible] During this time, consequential increased transpiration with soils of low available moisture, either due to frozen soil or lack of moisture, could have resulted in desiccation of upper plant parts. Below normal March temperatures followed, and this could also have resulted in freezing injury to plants that were possibly stimulated to growth activity during February. For the most part these conclusions support those of Schumaker and others (1979) and Hanson and others (1982).

Although the monthly accumulated percent of normal precipitation in areas of little or no winter injury was around 20 to 45 percent higher than in areas of extensive winter injury, the actual accumulated precipitation was nearly the same. This could indicate that snow cover was actually no greater and plant water deficits were probably just as high as in areas of winter injury. If this is true, it would seem to suggest that an underlying factor leading to winter injury of some of these shrubs, in addition to high water deficits and lack of snow cover, could be less selection for winter hardiness. For example, sagebrush in protected areas of usual snow cover and of the same subspecies as on an adjacent exposed site, may not be selected for winter hardiness to the same extent as their counterpart on the exposed site. This of course assumes other factors are equal. Frost penetration during inversions, for example, is likely greater in valley bottoms when there is little or no snow cover than on adjacent exposed slopes. Shrubs such as *Ceanothus velutinus* and *Arctostaphylos patula*, which are commonly damaged by winter injury, sprout from lower stems and the root crown and thereby survive without the need for extreme winter hardiness.

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Nelson, David L.; Tiernan, Charles F. Winter injury of sagebrush and other wildland shrubs in the Western United States. Res. Pap. INT-314. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 17 p.

Extensive winter injury of native wildland shrubs occurred in the Western United States during the winter of 1976–77. *Artemisia tridentata* was damaged most extensively followed by *Ceanothus* spp., *Arctostaphylos* spp., *Purshia* spp., and 32 other species of shrubs. The record low precipitation during this period, and consequential low snow cover in areas of normally heavy snow cover, combined with other factors that led to the injury.

KEYWORDS: Western U.S.A. shrub species, winter injury, winter desiccation, winter kill, winter freezing, drought damage

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LLAFFS – A Lightning-Locating and Fire-Forecasting System

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RESEARCH SUMMARY

This publication contains programs and documentation to implement an algorithm for calculating lightning fire probability. This calculation is based on a model originally developed for the National Fire-Danger Rating System. The model algorithm estimates the probability that a lightning discharge from cloud to ground will ignite a fire in fuels at the ground terminus of the lightning. Probability is estimated using variables that are measures of the fuel state and type, rain, and lightning. Details of the model can be found in Fuquay and others (1979), Latham (1979), and Fuquay (1980).

The lightning-locating and fire-forecasting (LLAFFS) system is designed to combine ignition probability with real-time lightning occurrence, and to transmit the results to the land manager. The lightning occurrence is assumed to be given by a Lightning Location and Protection, Inc., Position Analyzer in the form of a time, latitude, and longitude estimate for each lightning event in the area covered by the analyzer. The system programs use weather variables and the state of the fuels for the place the lightning hit ground; the algorithm is used to calculate the probability that the discharge started a fire. Probabilities are added with varying time scales to provide running totals that are recorded by the programs.

The land manager needs to know the location of probable fires. The transmission of this information must be cost-effective and the output convenient to use. We have developed a method for storing and transmitting lightning fire probability data using a simple printing terminal as a user interface device. The area occupied by a character on a printed page of text, called a pixel, is made to correspond to a geographical area on a map. An array of printed characters can thus be used with transparent overlays. The overlays "store" permanent information such as lookouts, roads, political boundaries, geographic features, equipment centers, areas of responsibility, or other desired data.

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LLAFFS
A Lightning-Locating and Fire-Forecasting System

Don Latham

1.0 INTRODUCTION

This publication contains programs and documentation to implement an algorithm for calculating lightning fire probability, developed at the Northern Forest Fire Laboratory, Intermountain Forest and Range Experiment Station. The calculation of lightning fire probability is based on a model originally developed for the National Fire-Danger Rating System. The model algorithm estimates the probability that a lightning discharge from cloud to ground will ignite a fire in fuels at the ground terminus of the lightning. Probability is estimated using variables that are measures of the fuel state and type, rain, and lightning. Details of the model can be found in Fuquay and others (1979), Latham (1979), and Fuquay (1980).

The lightning-locating and fire-forecasting (LLAFFS) system (figs. 1 and 2) is designed to combine ignition probability with real-time lightning occurrence, and to transmit the results to the land manager. The lightning occurrence is assumed to be given by a Lightning Location and Protection, Inc. (LLP) Position Analyzer in the form of a time, latitude, and longitude estimate for each lightning event in the area covered by the analyzer. The system programs use weather variables and the state of the fuels for the place the lightning hit ground; the algorithm is used to calculate the probability that the discharge started a fire. Probabilities are added with varying time scales to provide running totals that are recorded by the programs.

The land manager needs to know the location of probable fires. The transmission of this information must be cost-effective and the output convenient to use. We have developed a method for storing and transmitting lightning fire probability data using a simple printing terminal as a user interface device. The key to the method is that the area occupied by a character on a printed page of text, called a pixel, can be made to correspond to a geographical area on a map. An array of printed characters can thus be used with transparent overlays. The overlays "store" permanent information such as lookouts, roads, political boundaries, geographic features, equipment centers, areas of responsibility, or other desired data.

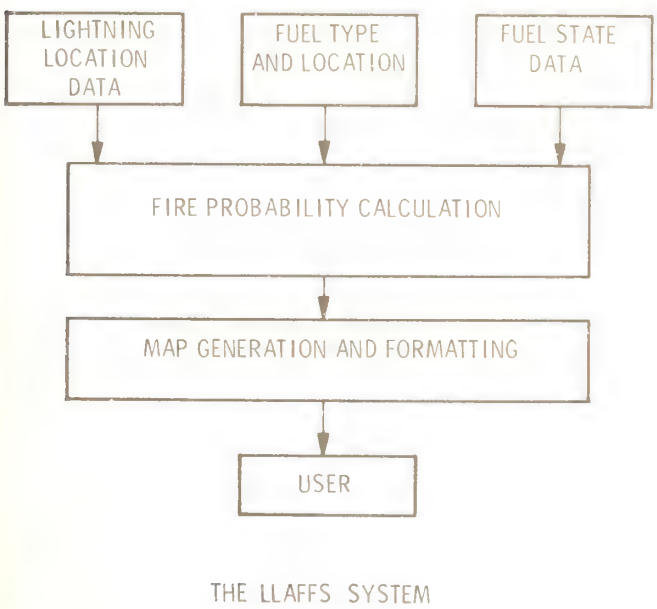


Figure 1.—Overall functional diagram of the LLAFFS system.

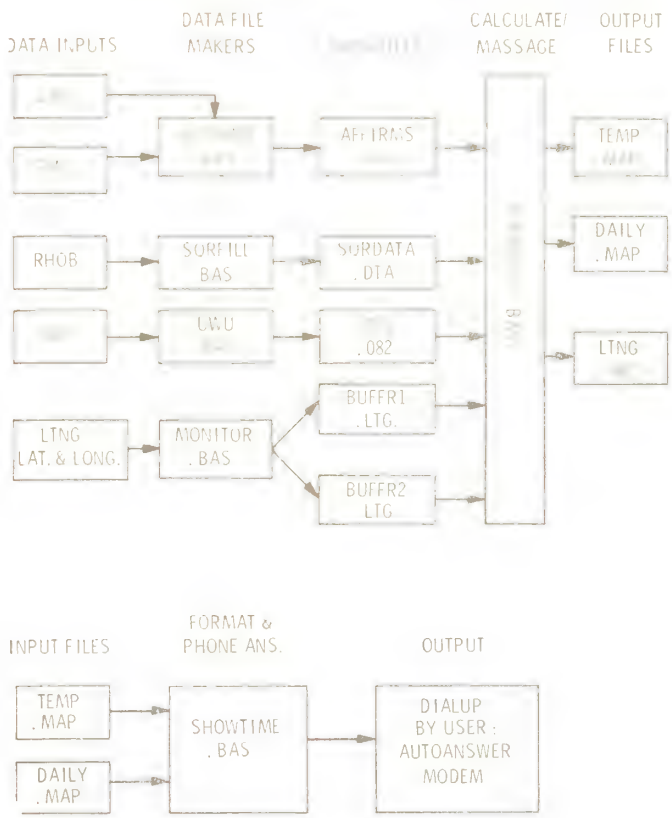


Figure 2.—Data flow, programs, and files of the LLAFFS system.

Figure 2 presents a data flow block diagram of LLAFFS. In use, the system runs as follows:

- The data file maker programs are periodically applied by the LLAFFS (not the field user) operator to provide current environmental data,
- which, along with real-time lightning location data, are turned into data files to be read by the probability calculation program,
- whose output files become input files to the "telephone operator,"
- which a field user calls on his/her terminal for the formatted fire probability data.

Our implementation of the LLAFFS system was done on a minicomputer. The programs, written in BASIC, were structured to match its capability for handling several programs and several users at the same time. If such a machine is not available, the programs may be adapted for use with a smaller machine, such as some of the commonly available microcomputers.

1.1 COMPUTING MACHINERY REQUIRED

The minimum machinery necessary to run LLAFFS would be a microcomputer, printer, and modem(s). This equipment will enable acquisition of AFFIRMS data, control of an LLP Position Analyzer (or reception of data from one), and output of printed data for local use with overlays Overlays also work very well on the front of CRT displays; even the printer might be unnecessary for some applications (although recommended). More than one modem will be required for dial-up access. Interrupt-driven software is necessary if a multitasking/multiuser operating system is not available.

The following sections of this package contain technical information for implementation. For an overview, the reader may skip to section 2.5.1.

2.0 INFORMATION FLOW: SYSTEM BLOCK DIAGRAM

Figure 2 presents the overall data flow for the LLAFFS system. The data inputs consist of Lightning Activity Level (LAL), fine fuel moisture (FFM), fine fuel bulk density (RHOB), upper windspeed (UWS), and lightning locations (in latitude and longitude) from the position analyzer. Only the lightning locations are on-line (real-time) inputs; the others are entered manually at the host computer. All information between system programs is passed through files.

2.0.1 Data Inputs—Geographical Assignment

The implementation of LLAFFS should begin by choosing a suitable overlay map scale, pixel size, and map limits (fig. 3). The map limits and pixel size are used by the computer programs only in PERIODIC.BAS (see 2.4.1 and flowchart, appendix C). The program SQRFILL.BAS (see 2.2.1) uses index numbers only and has no explicit geography. A guide map, or the overlay master map, must be used to decide the fuel types and AFFIRMS reporting stations to be used.

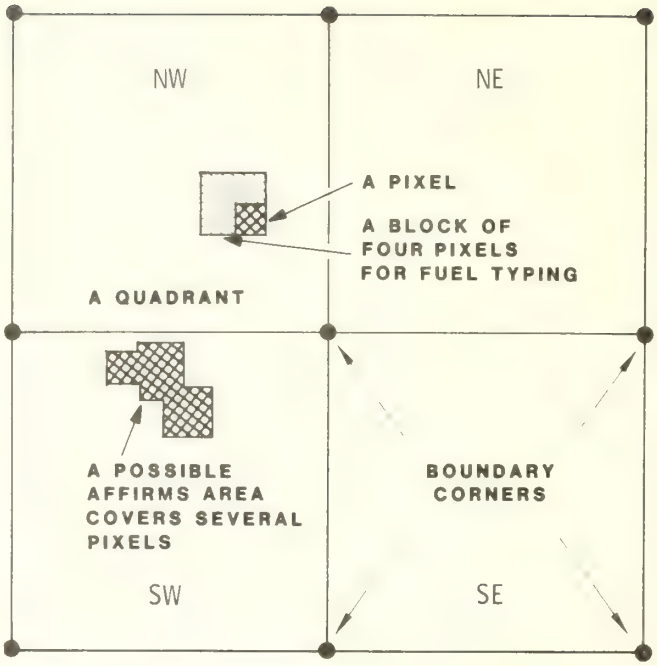


Figure 3.—LLAFFS system geometry/ geography.

2.1 DATA INPUTS DESCRIPTION

The ignition model requires Lightning Activity Level as one of its inputs. Fuquay (1980) explains the meaning of this number, and provides simple methods of estimation. Although the LAL specifies a number of lightning strokes, the actual number is used in computation. Another variable required is the steering windspeed for storms in the area of interest. The Weather Service standard 500-millibar windspeed can be used with little error. The fuel bulk density can be estimated as shown in Fuquay and others (1979). This variable is important in the calculation; be sure it is as accurate as possible. If none of the fuel models described in table 5 of the above paper fits exactly, however, the closest approximation will have to do. In general, RHOB for long-needled conifers will be 4 pounds per cubic foot, short-needled conifers 6 to 8, grass 2, and broadleaf species 4. The remaining input variable, fine fuel moisture, is available from AFFIRMS or is calculated according to the National Fire-Danger Rating System. If a different rating system is in use, then some means of conversion to the NFDRS 1-hour timelag moisture content must be applied.

2.2 DATA FILE MAKERS

The data file maker programs are used to set up the LLAFFS system and update some of its inputs. We will discuss the programs in the order in which they are applied in use. The flowcharts and program printouts can be found in appendix C. **Note that all LLAFFS files except SQRDATA.DTA must be externally created at the initial implementation of the system.**

2.2.1 SQRFILL.BAS

This program creates a file SQRDATA.DTA, which contains a bulk density (RHOB) and AFFIRMS station code number for each of the pixels. The pixels are grouped into blocks of four (fig. 3). Each block of four has an AFFIRMS station assigned to it. Some stations will be assigned to more than one block. The stations are chosen by the user to be most representative for Lightning Activity Level and fine fuel moisture data. This program will probably be used very seldom, because the bulk densities for the pixels, as well as AFFIRMS stations, will not change appreciably over a season and probably very little from season to season. For this reason, SQRFILL is not a very "user friendly" program. Details of the file format are in section 2.3.2.

2.2.2 AFFIRMS.BAS

This is a program which prompts the user to enter LAL and FFM values for each selected AFFIRMS reporting station in the area covered by the maps. The number of stations will vary by the application (fig. 3). Our application used 73 stations. Several pixels on a map may use FFM and LAL information from the same AFFIRMS station (2.2.1). The file AFFIRMS.082 is updated and passed to PERIODIC.BAS. PERIODIC.BAS, by knowing a pixel's AFFIRMS station code number, assigns the appropriate values of FFM and LAL to a pixel. We wished to keep a running record of the AFFIRMS data. Because of this, the file AFFIRMS.082 can be extended each time AFFIRMS.BAS is run. It is unlikely that this will be desired in most applications, so we have provided for rewrite or append functions in this program. If data files are not desired, answer "R" (rewrite) at the "Rewrite (R) or Append (A)" prompt. Choice of rewrite mode will wipe out all data that may have been filed from previous append mode operations, so take care here.

2.2.3 UWU.BAS

UWU.BAS creates a file called UWU.082, which is used when PERIODIC.BAS updates the upper windspeed variable. In general, the upper windspeed value will be the same for most of the pixels. The version of the program given here passes, to UWU.082, the current values of the upper windspeed at three stations and the date and time. The actual calculation of the UWS values for each pixel is done in PERIODIC.BAS. As with AFFIRMS.BAS, we have an append or rewrite choice. The rewrite choice will wipe out any data left from previous append mode operation. Take care when answering "Append (A) or Rewrite (R)" if data files are to be kept.

2.2.4 MONITOR.BAS (SUPERMON.BAS)

The lightning data from an LLP Position Analyzer is received and filed by this program. In our application, MONITOR is an interactive task running on a multitasking machine. There is more than one input data stream for lightning data in this version of the monitor program, as well as some communication with other computers. Our program is included in the package for completeness and as an example for generating the buffer files in the correct format for PERIODIC.

The lightning data go into one of two buffer files, as input for PERIODIC.BAS. These files, BUFFR1.LTG and BUFFR2.LTG (2.3.4), are necessary to prevent loss of data during the running of PERIODIC. If the machine running these programs is not multitasking, then a different MONITOR will be necessary to prevent lost lightning data. One possibility is an interactive program to take advantage of the core storage in the Position Analyzer. Other schemes depend on the available hardware.

2.3 DATA FILE DESCRIPTIONS

As we have seen, there are five intermediate data files within the LLAFFS system. These contain the updated values of the input variables. The files are inputs to the probability predictor and output file maker program, PERIODIC.BAS. Depending on the type of computer being used as the host, the data files may be updated interactively at any time, except when PERIODIC is reading them (2.2.4, 1.1). We will describe the file contents in the order shown in figure 2.

2.3.1 SQRDATA.DTA

This file, created within SQRFILL.BAS, contains encoded bulk density and AFFIRMS station code numbers for each block of a 24 by 24 array, hence its length of 576. The number of blocks depends on the implementation. Each record contains a number that tells PERIODIC.BAS which AFFIRMS data station and RHOB index are to be used. Each square is representative of a block of four pixels in the final map. Both pieces of information are combined into a single number in the file. The form of this number is (station number * 100) + RHOB index.

2.3.2 AFFIRMS.082

The first record in this file is the record number of the last record written. The subsequent data items are packed into nine records; they contain the latest data produced by AFFIRMS.BAS. The first value in the nine records is the time in minutes from January 1 of the year that the AFFIRMS data was measured. Next are values for FFM and LAL, one for each reporting weather station. These values are coded (multiplexed) by AFFIRMS.BAS into a single number for each station for efficient packing. The form of this number is (LAL * 100) + FFM. The number of AFFIRMS stations will vary according to the application; we used 73. It is important to note that the number of variables is not the same as the number of records in the file; there are nine records, one for each BASIC "outfile" statement. If the rewrite mode is chosen, the file is wiped clean; any data that has been entered in append mode will be lost.

2.3.3 UWU.082

As with AFFIRMS.082, this file, created externally at implementation, can either be appended to or rewritten. The number of records depends on whether the append mode or the overwrite mode is used in UWU.BAS. The first record contains the record number of the beginning of the latest data written. Then follows a record with the calculated local time in minutes since the beginning of the year that

the observations were taken (as in AFFIRMS.082) and three wind speeds. A different time code scheme can be used. The appended file will grow continuously. If the rewrite mode is chosen at any time, all data from an appended file will be lost.

2.3.4 BUFFR1.LTG and BUFFR2.LTG

These are two identical files containing lightning data to be read by PERIODIC. They are identical in format, and random in length. They must be initially created at implementation of LLAFFS. They are alternately read and flushed so that the maximum size of either would be in the neighborhood of 2,000 78-byte records.

2.4.1 PERIODIC.BAS—The Main Program

PERIODIC.BAS (fig. 4) is the workhorse for LLAFFS. This program, running as a background task, performs the following functions:

(1) takes in the values of the input variables (RHOB, FFM, LAL, UWS) from the AFFIRMS.082, SQRDATA.082, and UWU.082,

(2) takes in lightning data from BUFFR1.LTG and BUFFR2.LTG,

(3) gets the appropriate values of variables and lightning for each pixel from the files,

(4) calculates the probability of ignition per discharge in each pixel,

(5) updates the half-hour (or other selected interval) maps,

(6) updates the cumulative (daily) maps, and

(7) generates archival files.

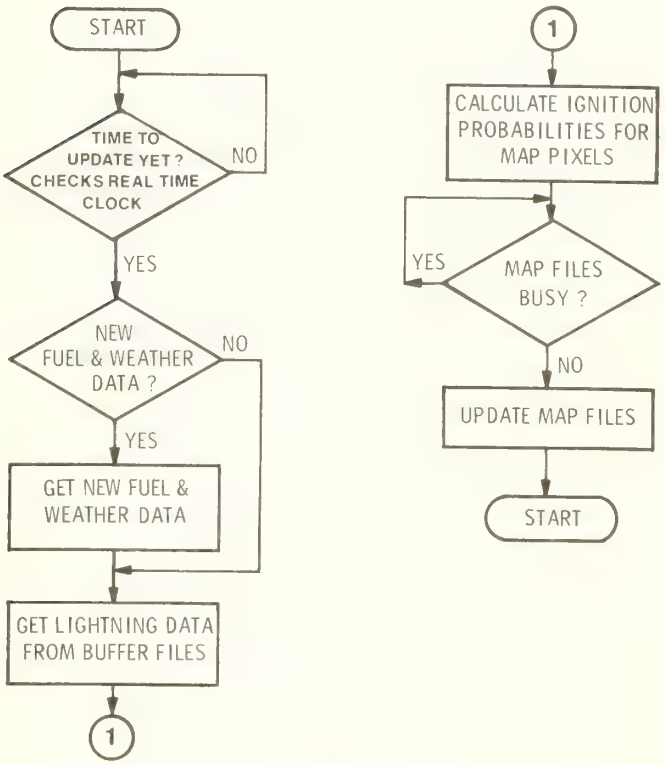


Figure 4.—PERIODIC.BAS functional diagram.

Input files to PERIODIC are discussed in section 2.3. The output files (see 2.4.2) are TEMP.MAP, DAILY.MAP, and LTNG.082. PERIODIC also uses four files for temporary storage as it runs. These are BUFR.MAP, LTOTL.DTA, and HALFHR.CNT. The temporary files are created when the system is implemented. The first of these temporary files is used in merging the last interval's data with the DAILY.MAP file. The second, LTOTL.DTA, contains total lightning strikes for pixel groups. The third, HALFHR.CNT, contains the lightning counts by pixel for the last half-hour time period. This file is put in BUFR.MAP and a new HALFHR.CNT is calculated. The fourth file contains communications between PERIODIC and MONITOR to tell MONITOR which lightning location buffer file (see 2.3.4) to use.

The host computer must have a real-time clock so that PERIODIC will know what time it is. The update interval and the beginning-time of the 24-hour DAILY.MAP file are set in PERIODIC. For optimum machine use, PERIODIC should be called from an interrupt routine in the operating system, instead of having a loop as our version does. Indeed, if the system is to be installed on a non-multitasking machine, MONITOR must be the control program, running all the time, and contain a call to PERIODIC. The two programs can call each other using a chain command because all information is passed in files. A single-user machine may lose some data during the PERIODIC running time, unless interrupt-driven software has been devised.

2.4.2 PERIODIC.BAS Output Files

PERIODIC.BAS (figs. 2 and 4) uses three output files, TEMP.MAP, DAILY.MAP, and LTNG.082. The files are created externally when LLAFFS is implemented. The last is archival and will not be discussed. TEMP.MAP contains the latest half-hour counts and DAILY.MAP the cumulative count for the current day. The beginning of the day is set in PERIODIC.

The structure of TEMP and DAILY are shown in figure 5. Each record after the first five contains three variables. The first is the row and column of the pixel to which the data belong. The second variable is the number of lightning discharges that the location equipment claims has struck the ground in the area represented by the pixel. The third is the probability per discharge of an ignition in the area represented by the pixel. The product of probability per discharge and the number of discharges, although not exact, is used for the probability that an ignition will occur within the ground area represented by the pixel.

A listing and flowchart for PERIODIC are in appendix C.

2.5 SHOWTIME.BAS, The Output Program

SHOWTIME (figs. 3 and 6) is designed to read the output files DAILY.MAP and TEMP.MAP and format them into printer-compatible form for output to the user. A listing and detailed flowchart of SHOWTIME are included in appendix C.

The program has been optimized to reduce printing time to a minimum. Rows in the output map having no data are output as a carriage return-linefeed pair. The row is truncated at the last pixel having data in it. Maps with no data are not printed, and a "no data" statement is output in place of the map.

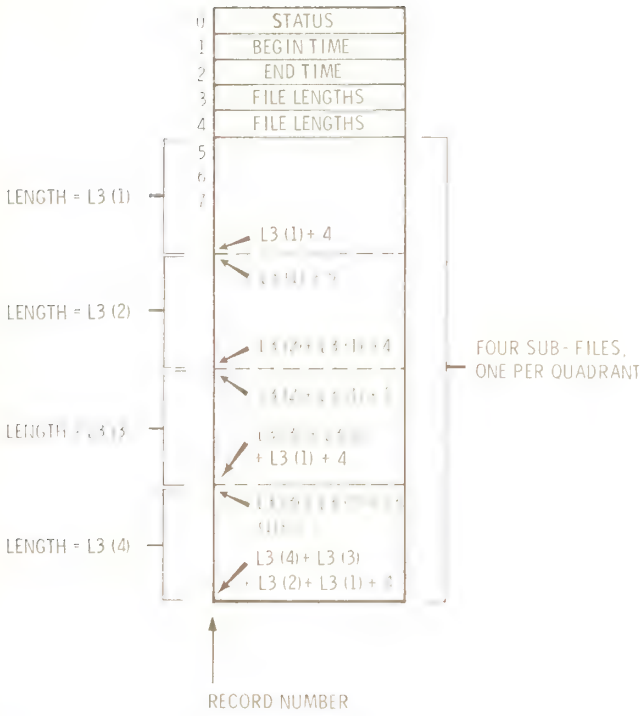


Figure 5.—DAILY.MAP and TEMP.MAP file structure.

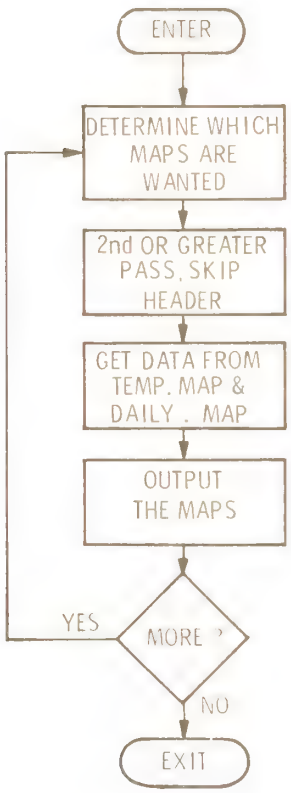


Figure 6.—SHOWTIME.BAS functional diagram.

2.5.1 OUTPUT FORMAT

Examples of SHOWTIME.BAS output are shown in figures 7 and 8. In these examples, each pixel represents an area on the ground of about 3 miles by 3 miles. There is, of course, nothing sacred about this size—it can be changed by altering the programs (see 2.0.1) and overlay maps to suit the occasion.

The lightning density map (fig. 7) is straightforward. An "X" is placed as an index mark in the upper and lower left corners of the printout. The index mark is keyed to the overlay. Each pixel contains a number. This is the number of strikes the location system says have hit within the corresponding overlay area on the ground. Zeroes are suppressed, and more than nine strikes in a pixel is represented by an "*". The time period is specified in the text accompanying the printed map.

The fire probability map (fig. 8) is almost as simple. The numbers do not indicate the number of fires expected in each pixel. The numbers are codes representing the probability of a fire being in the pixel. We have tentatively set them as follows: a blank is zero probability, a "1" means probability between 0 and 0.2 or a 20 percent chance of a fire, a '2" is between 0.2 and 0.4 or between 20 and 40 percent, a "3" is between 0.4 and 0.8 or between 40 and 80 percent, and a "4" means that there is a probability greater than 0.8 or 80 percent that there is a fire in the pixel. This coding enables us to put the probabilities in a single number for the pixel. Users who prefer a different coding scheme or levels are welcome to do so, provided the actual calculation of the probabilities is not changed. The values are set in a subroutine within SHOWTIME.

Information on the printout could also represent other variables related to an area on the ground, if the variables can be represented as a single character. The generation of extra information would go into SHOWTIME. A possible use might be a simple fire-danger map, or a rate-of-spread code. To do this, more files and additions to PERIODIC would have to be created.

2.5.2 Warning

Research indicates that the accuracy of the lightning ground strike points is not routinely better than the 3 miles we have used for our pixel size. Indeed, in some cases the error may be larger than twice that amount. This means that the lightning locations and fire probabilities may be "off" by at least one pixel, possibly more, in any direction. More research is being done on accuracy.

THIS IS THE SOUTHWEST CUMULATIVE LIGHTNING MAP.
THIS MAP COVERS THE PERIOD
FROM : 08/11 11:00 (MDT)
TO : 08/12 09:40 (MDT)
THERE WERE 296 STRIKES IN THE QUADRANT.

Figure 7.—A typical lightning density map generated by SHOWTIME.

THIS IS THE SOUTHWEST CUMULATIVE EXPECTED FIRE MAP.
THIS MAP COVERS THE PERIOD
FROM : 08/11 11:00 (MDT)
TO : 08/12 09:40 (MDT)
THERE WERE 230 SQUARES EXPECTING FIRES.

Figure 8.—A typical fire probability map generated by SHOWTIME.

2.6 FIELD USE

The field user (Forest level) will need a set of instructions for use of LLAFFS. The instructions we used for our field trial are included as appendix A. The important elements of these instructions are:

- Dial-up or other access instructions must be clear and detailed; a lot of inquiries and "handholding" will be saved by overkill in the instructions.
- The map areas covered by the printout pixels must be clearly stated and related to familiar geography.
- Overlays must be simple and easily read. More than one overlay map covering the same area is better than a single one with too much information on it.
- The meanings of the numbers on the printouts must be clearly stated.

Overlays for our application are not included in this package because of their cost and provinciality. We have had some success with overlays made from simple hand-drawn maps such as that of figure 9. These are copied using a transparency copier such as those used for making overhead projections. If desired, information to help users with this procedure might be given as part of the field guide. Transparencies may have to be tailored for use with varying kinds of terminals, because terminal print sizes are variable. If the users are using only one terminal or one kind of terminal, this tailoring will not be necessary.

Appendix B contains a sample user run of the LLAFFS output. The message section at the beginning of the run is generated by the operating system of our host computer. If this is desired in other implementations, it could be part of SHOWTIME. To avoid modifying the program each time the message is to be changed, put the message in a file and access it in the SHOWTIME program.

2.7 CONCLUSION

The programs which are included in this package were all developed in BASIC for use on a Perkin-Elmer 3200 machine. Adaptation to other computers may require some program rewriting. In particular, file handling syntax may be considerably different. Smaller machines may require more intermediate files because of memory limitations. It may also be desirable to automate the map output instead of having a dial-in system. See also the comments in sections 1.1 and 2.2.4.

NOTE: Portions of the programs having to do with probability calculation must not be changed without consultation. To make such changes will invalidate the predictions. If this warning is heeded, the system presented in this package will improve the use of lightning location networks for fire management.

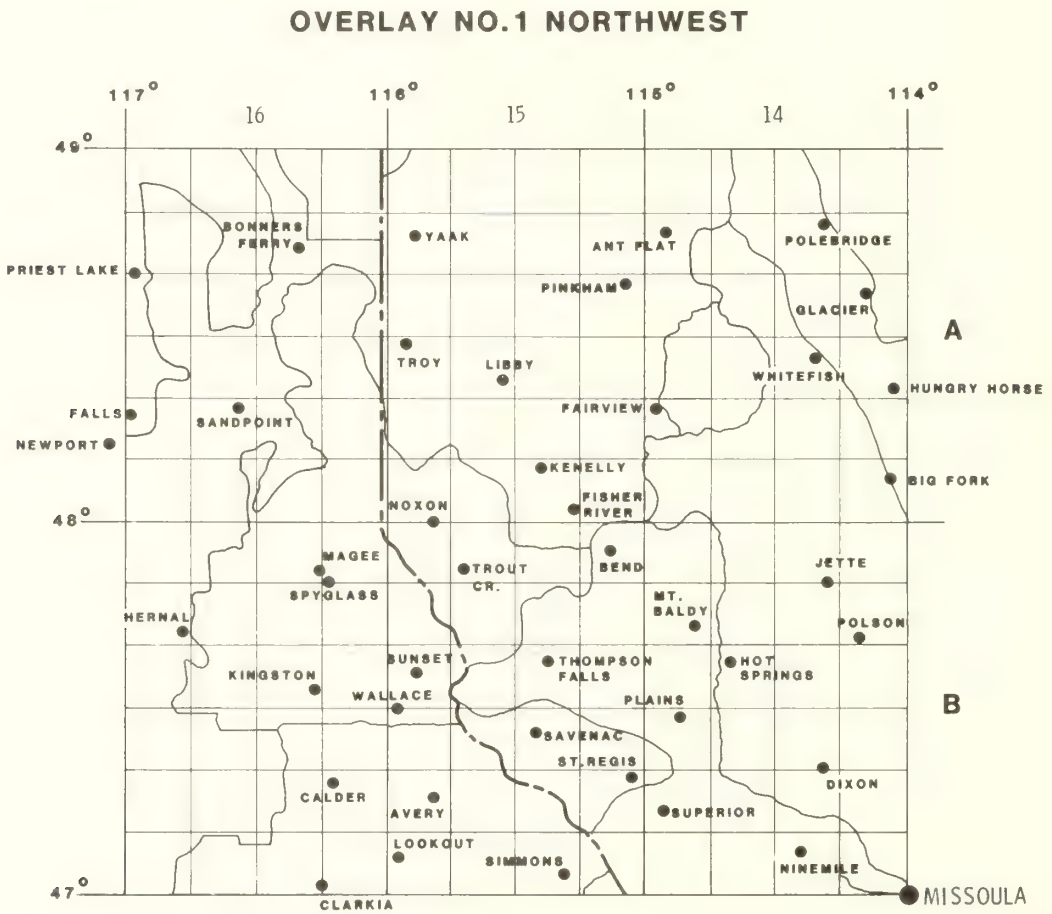


Figure 9.—A sample overlay map.

PUBLICATIONS CITED

Fuquay, D. M.; Baughman, R. G.; Latham, D. J. A model for predicting lightning-fire ignitions in wildland fuels. Res. Pap. INT-217. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1979. 21 p.

Fuquay, D. M. Forecasting lightning activity level and associated weather. Res. Pap. INT-244. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1980. 30 p.

Latham, D. J. Progress toward locating lightning fires. Res. Note INT-269. Ogden, UT: U. S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1979. 6 p.

APPENDIX A
SAMPLE INSTRUCTIONS*

Dialin Lightning

This is the instruction sheet for using experimental lightning location and fire probability maps. The maps are a joint effort between Aviation and Fire Management of Region 1 and the Intermountain Forest and Range Experiment Station, Northern Forest Fire Laboratory. Our objective is to make available both current and cumulative information on lightning occurrence and probable fire starts. The information is in the form of simple printouts designed to be used with a Regional overlay map. The computer that generates the printouts is located at the Fire Laboratory. The Regional Coordinator's office plans to alert users through the Weather teletype network, and distribute the maps and instructions for use. The printouts can be obtained using a 300-baud printing terminal, such as an Execuport. The terminal may have either 80 or 132 print columns. The printouts, an example of which accompanies these instructions, are designed to be used with the overlay maps, also supplied.

The Regional overlay map has been divided into four quadrants: NW, NE, SW, and SE. The center of the quadrants is at 47 degrees north latitude and 114 degrees west longitude. Each quadrant covers two degrees in latitude and three in longitude:

NORTHWEST: 47–49 N and 114–117 W, includes part or all of the Kaniksu, Kootenai, Flathead, Coeur D'Alene, Lolo, and St. Joe Forests,

NORTHEAST: 47–49 N and 111–114 W, includes the Flathead, Lewis and Clark, Lolo, and Helena Forests,

SOUTHWEST: 45–47 N and 114–117 W, includes the St. Joe, Clearwater, Lolo, Nezperce, and Bitterroot Forests,

SOUTHEAST: 45–47 N and 111–114 W, includes the Lolo, Helena, Deerlodge, Beaverhead, and Gallatin Forests.

The printouts are made with an X in each of the upper and lower left-hand corners. These are to be aligned with the leftmost top and bottom boundary corners of the appropriate quadrant of the overlay map. For example, if the quadrant on the printout is the NE, the top X goes under 49N, 114W and the bottom X under 47N, 114W and so on. Those of you with map experience will note that the registration of the overlay and the map is not perfect. That is because the printouts are "flat earth" and the maps are projections. Expect errors of at least one pixel (that is jargon for one character space on the printout map) in all directions, and more toward the top of the upper half of the overlay and the bottom of the lower half.

There are 16 available printout maps, 4 for each quadrant. These are:

- a lightning occurrence map updated each half-hour,
- a cumulative lightning map, beginning each day at 040 hours,
- a fire probability map updated each half hour, and
- a cumulative fire probability map, beginning each day at 0400 hours. The numbers on the lightning maps represent the number of discharges to the area represented by that pixel (one character space), for both the 1-hour and th cumulative maps.

The fire probability maps have been scaled. The probability of fire for each pixel is reduced to a single number from zero to four. The zeroes are not printed for better cla ity. These characters do not translate directly into numbe of fires. That is, a "1" in a pixel does not mean one fire in that area, rather a low but not zero probability of a fire. Th same is true for a "2", and so on. The larger the number, the greater the chance that there is a fire near the area represented by the pixel. Remember that this area is large than it appears because of the accuracy limitations of the equipment and the overlay display technique.

Now, how can you get the maps? That is the easy part. First, get hold of a 300-baud terminal that can hook up to phone line. Then, dial 329-3870, commercial, or 585-3870 FTS. When you hear the tone, stick the phone in the termi nal (if it is that kind). Type a few letters and hit return; the message *SIGNON REQUIRED should appear. If it does not, the computer is down or the terminal is not making contact. Try once more, and if there is no response, the computer is probably down.

If the message *SIGNON REQUIRED, followed by a new line beginning with an *, is received, type in SIGNON ID,125,LTNG, then return. Do not forget the commas, and do not leave any spaces except for one after the word SIGNON. Put the forest ID initials in position ID or some other ID letters for other users. Do not use numbers. ID may be from one to four letters long. The computer will respond with the program SHOWTIME, which begins with the date and time and should proceed as shown in the examples we have provided. Some time may elapse before the response, but a minus sign (–) will appear right away to show that you are hooked up. If you have difficulties an have struggled with them for a while, call us at 585-3494, FTS, or 329-3494, commercial. If the computer is down, tr later.

Please remember that this is an experiment. We are not staffed for a 7-day week, 24-hour day, but we will do the best we can. We would like to have your comments. Either pass them through the Regional dispatch center or send them directly to Don Latham at the Northern Forest Fire Laboratory. We are especially interested in documented comments regarding accuracy.

**Note*: These sample instructions are from an experiment and are for user guidelines only. Telephone numbers are now different, and LLAFFS is no longer experimental.

APPENDIX B
A SAMPLE FIELD RUN OF LLAFFS

```
SIGNON REQUIRED
SIGNON ACCEPTED
>SIGNON DON,JPS,LLAFFS

-08/12/82  10:24:32
-
  LIGHTNING LOCATION AND FIRE FORECAST SYSTEM (LLAFFS)
-
-NEWS     08/11/82
-ALL SYSYTEMS GO.
-
-WHICH QUADRANT WOULD YOU LIKE TO USE ? (NW,NE,SW,SE)
>SW

    OPTIONS
      LIGHTNING MAPS
        1. LAST HALF HOUR
        2. CUMULATIVE
      EXPECTED FIRE MAPS
        3. LAST HALF HOUR
        4. CUMULATIVE
      OTHERS
        5. 1 AND 2
        6. 3 AND 4
        7. 2 AND 4
ENTER AN OPTION NUMBER
>7
```

THIS IS THE SOUTHWEST CUMULATIVE LIGHTNING MAP.
THIS MAP COVERS THE PERIOD
FROM : 08/11 11:00 (MDT)
TO : 08/12 09:40 (MDT)

THERE WERE 296 STRIKES IN THE QUADRANT.

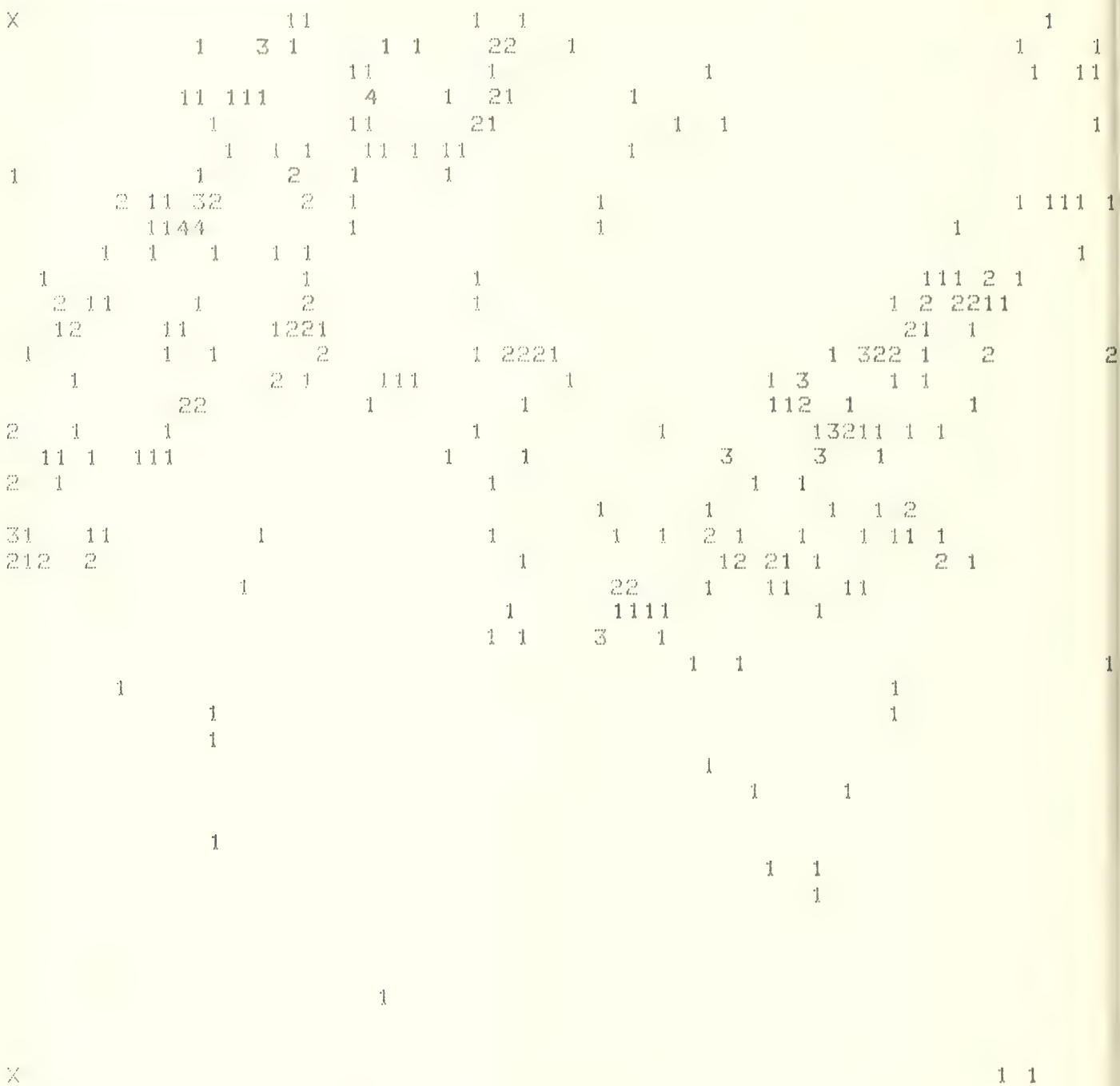
```
THIS IS THE SOUTHWEST CUMULATIVE EXPECTED FIRE MAP.
THIS MAP COVERS THE PERIOD
FROM :   08/11     11:00     (MDT)
TO   :   08/12     09:40     (MDT)
**********************************************************************

X
```



```
THERE WERE  230  SQUARES EXPECTING FIRES.
**********************************************************************
MORE MAPS ?  (Y OR N)
>Y
WHICH QUADRANT    (NW,NE,SW,SE)
>SW
OPTION NUMBER
>7
```

THIS IS THE SOUTHEAST CUMULATIVE LIGHTNING MAP.
THIS MAP COVERS THE PERIOD
FROM : 08/11 11:00 (MDT)
TO : 08/12 09:40 (MDT)

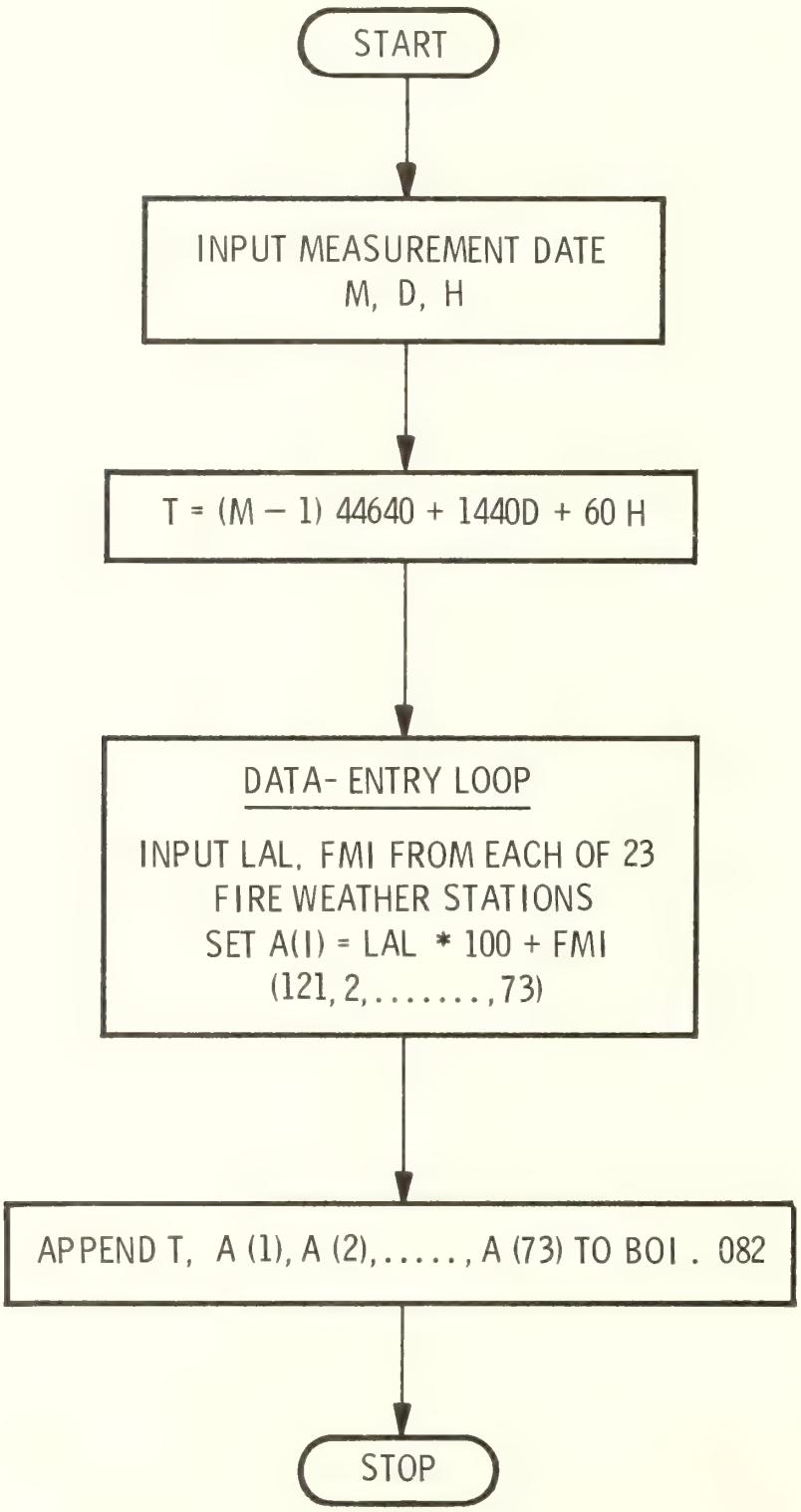


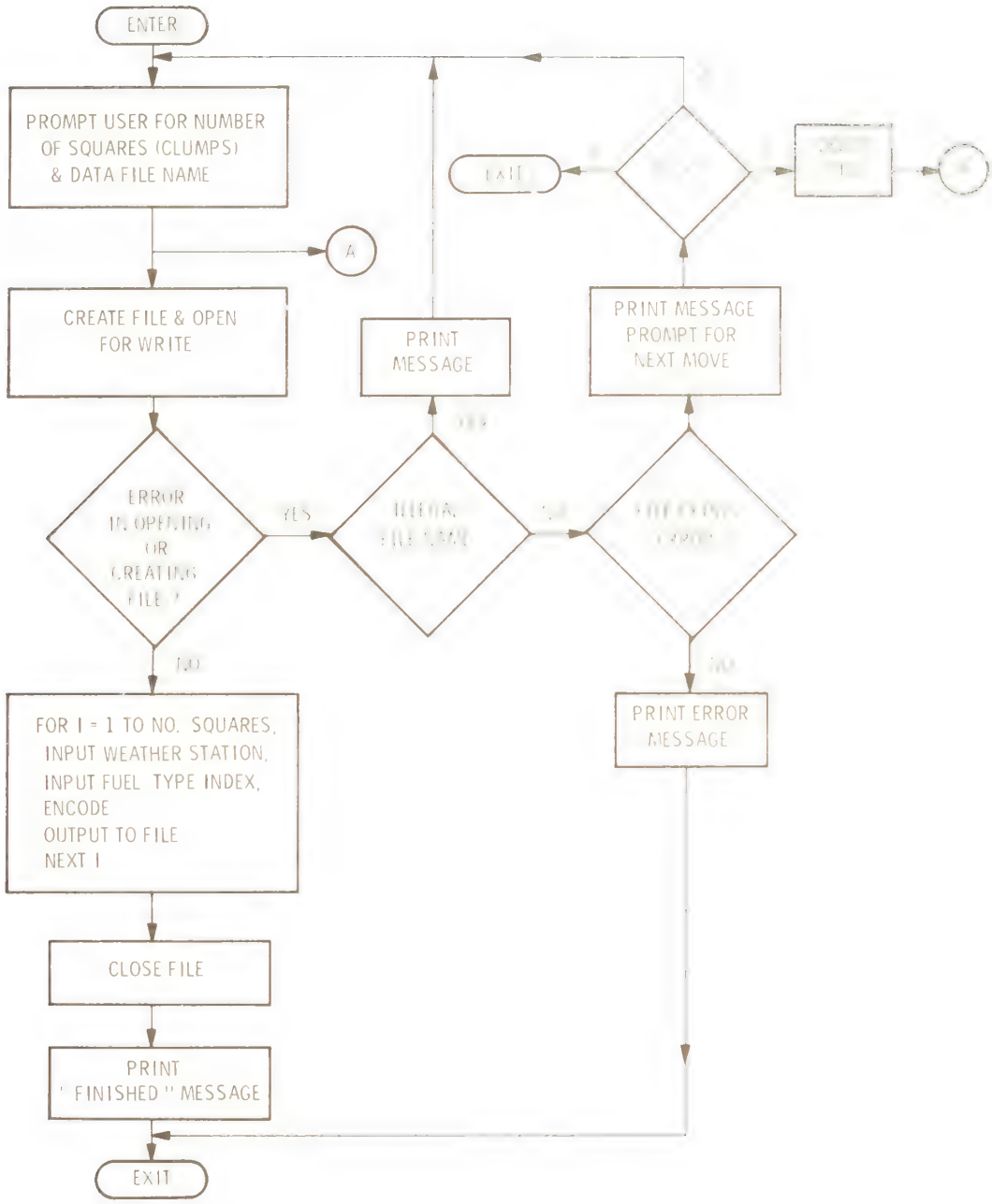
THERE WERE 313 STRIKES IN THE QUADRANT

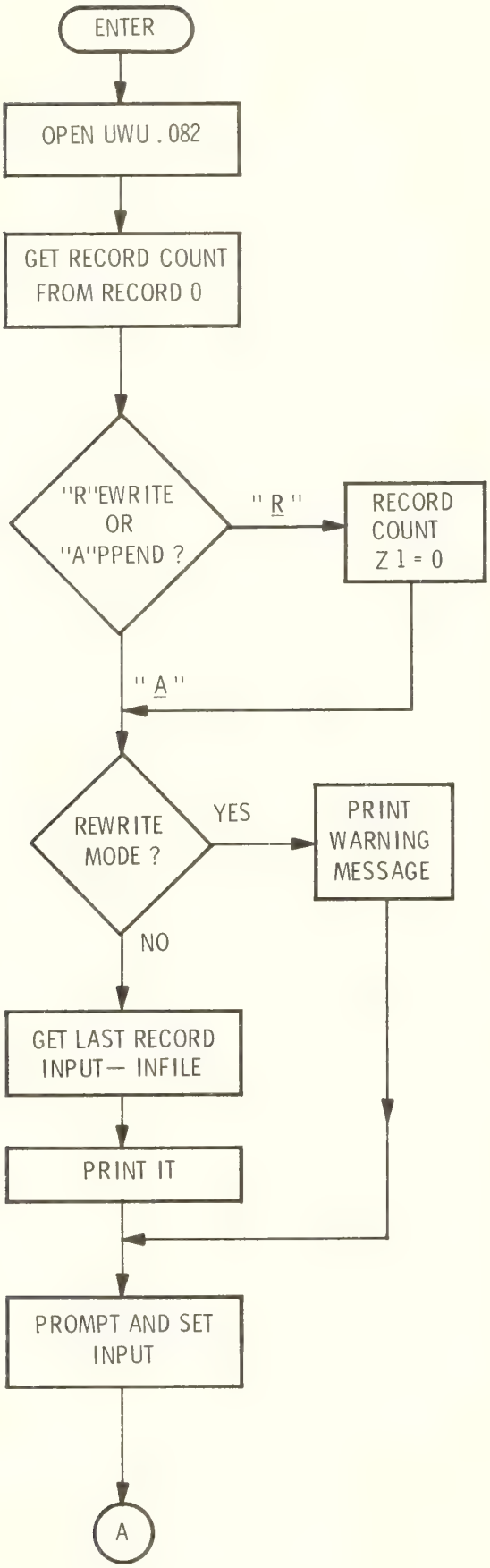
THIS IS THE SOUTHEAST CUMULATIVE EXPECTED FIRE MAP
THIS MAP COVERS THE PERIOD
FROM : 08/11 11:00 (MDT)
TO : 08/12 09:40 (MDT)
THERE WERE 243 SQUARES EXPECTING FIRES.

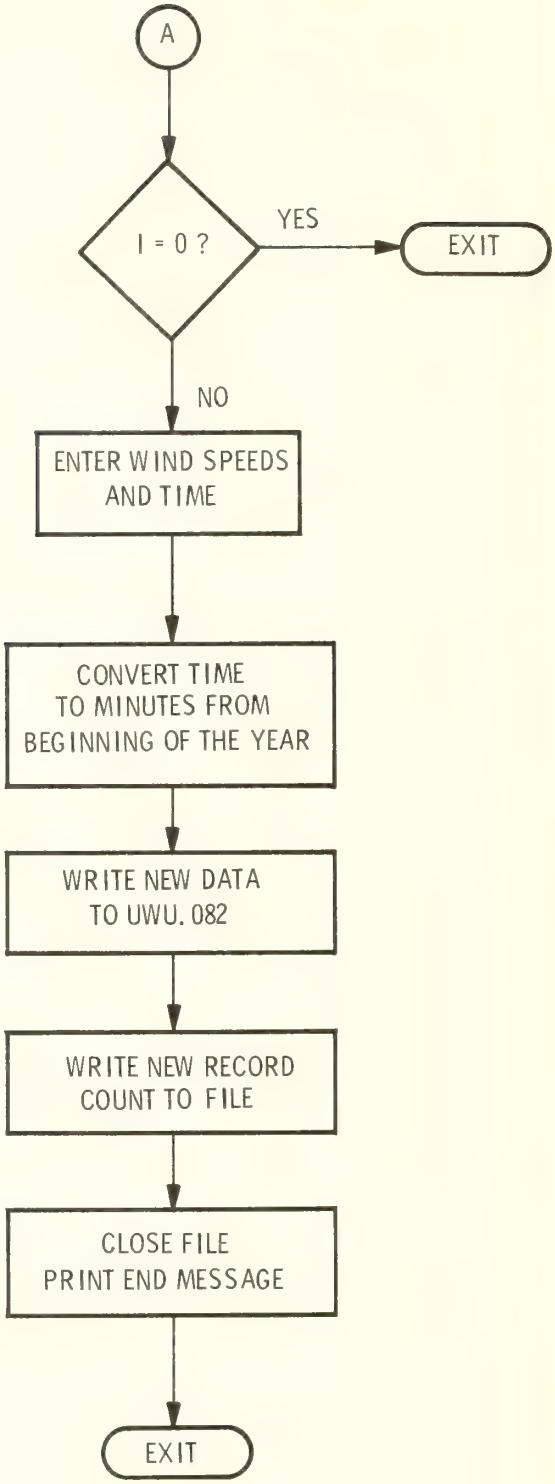
APPENDIX C
FLOW CHARTS AND PROGRAMS

AFFIRMS DATA UPDATER

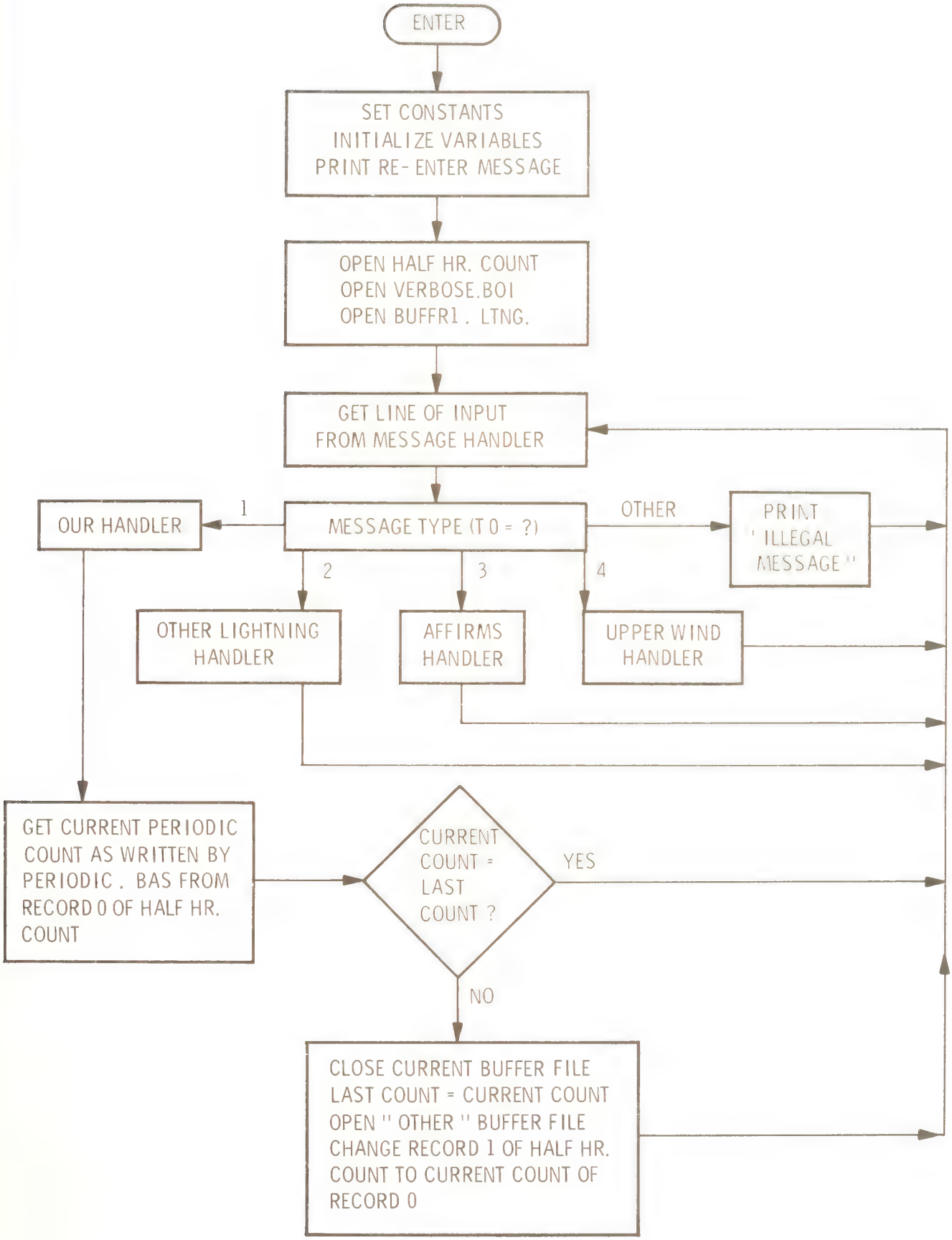

START
INPUT MEASUREMENT DATE
M, D, H
T = (M − 1) 44640 + 1440D + 60 H
DATA- ENTRY LOOP
INPUT LAL, FMI FROM EACH OF 23
FIRE WEATHER STATIONS
SET A(I) = LAL * 100 + FMI
(121, 2, ... , 73)
APPEND T, A (1), A (2), ... , A (73) TO BOI . 082
STOP


ENTER
PROMPT USER FOR NUMBER OF SQUARES (CLUMPS) & DATA FILE NAME
A
CREATE FILE & OPEN FOR WRITE
ERROR IN OPENING OR CREATING FILE ?
YES
NO
PRINT MESSAGE
PRINT MESSAGE PROMPT FOR NEXT MOVE
PRINT ERROR MESSAGE
FOR I = 1 TO NO. SQUARES,
INPUT WEATHER STATION,
INPUT FUEL TYPE INDEX,
ENCODE
OUTPUT TO FILE
NEXT I
CLOSE FILE
PRINT " FINISHED " MESSAGE
EXIT


ENTER
OPEN UWU . 082
GET RECORD COUNT FROM RECORD 0
"R"EWRITE OR "A"PPEND ?
" R "
RECORD COUNT Z 1 = 0
" A "
REWRITE MODE ?
YES
PRINT WARNING MESSAGE
NO
GET LAST RECORD INPUT— INFILE
PRINT IT
PROMPT AND SET INPUT
A


A
I = 0 ?
YES
EXIT
NO
ENTER WIND SPEEDS AND TIME
CONVERT TIME TO MINUTES FROM BEGINNING OF THE YEAR
WRITE NEW DATA TO UWU. 082
WRITE NEW RECORD COUNT TO FILE
CLOSE FILE PRINT END MESSAGE
EXIT

SUPERMON . BAS



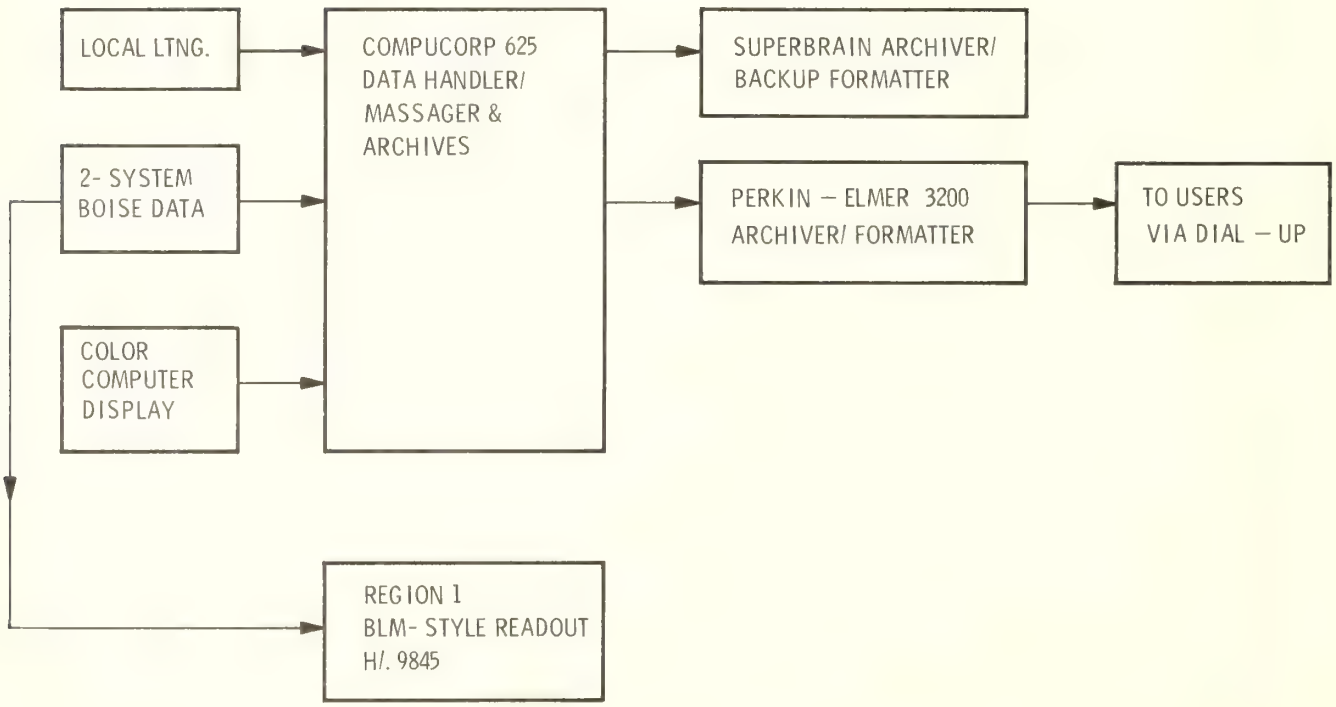
OUR HANDLER → WRITES INPUT ASCII LINE, PA PROGRAM 0 OUTPUT, WITH MONTH AND DAY TACKEDON, TO THE CURRENT BUFFER FILE

OTHER HANDLER → SAME AS ABOVE, BUT WRITES TO VERBOSE . BOI FILE

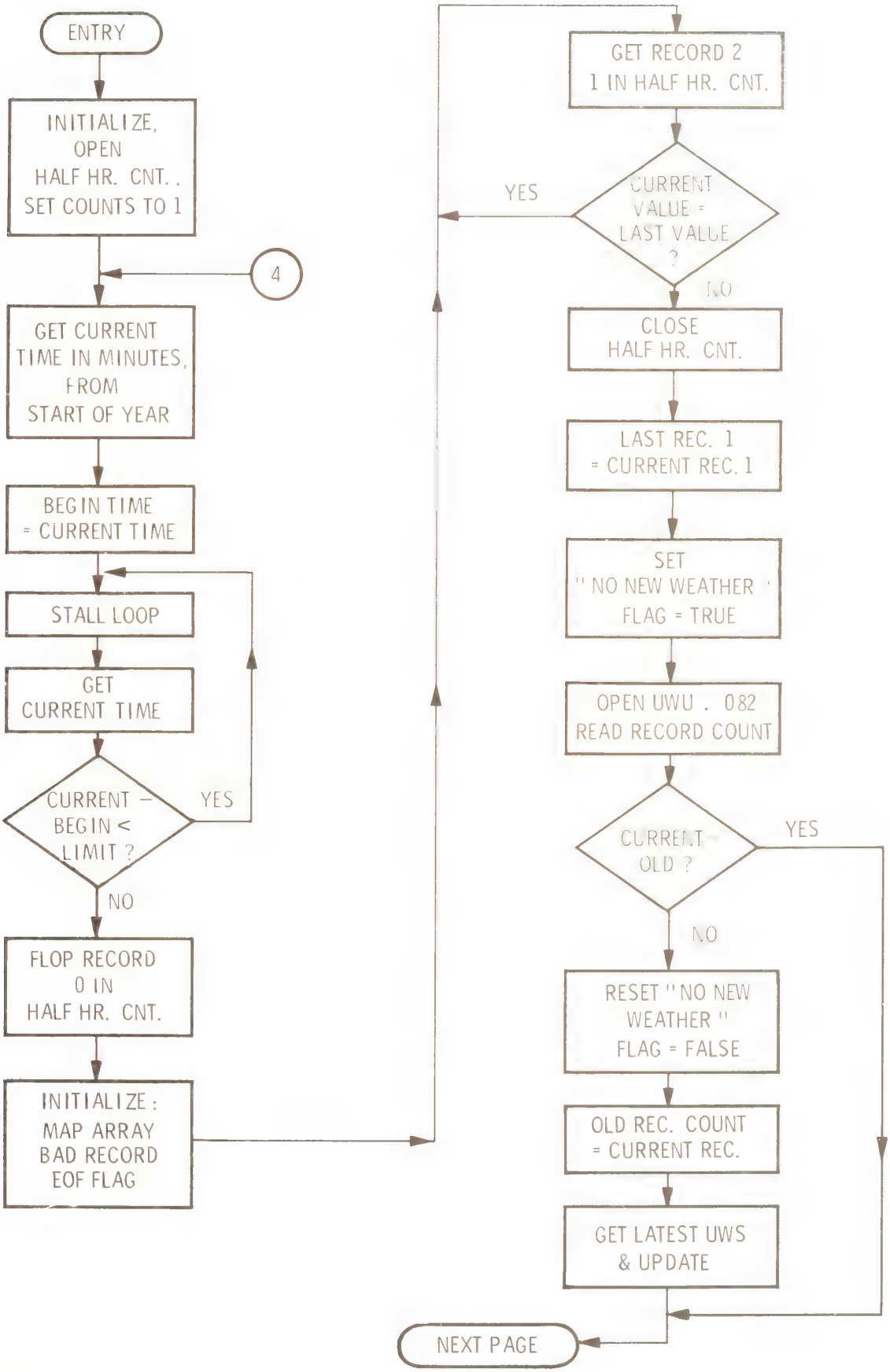
AFFIRMS HANDLER → PASSES AFFIRMS DATA AROUND OUR SMALL COMPUTER NETWORK

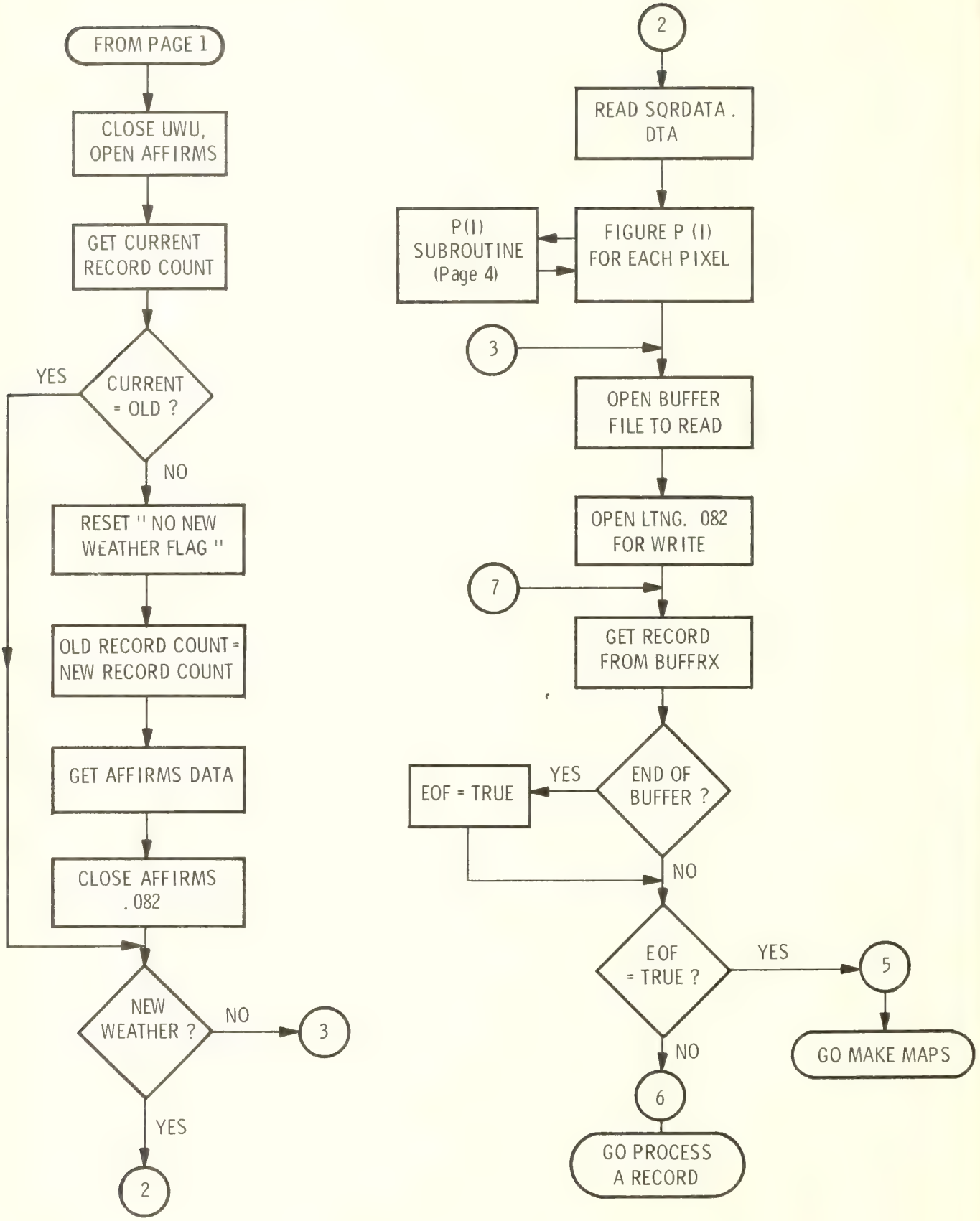
UPPER WIND HANDLER → PASSES UWSPEED DATA AS ABOVE

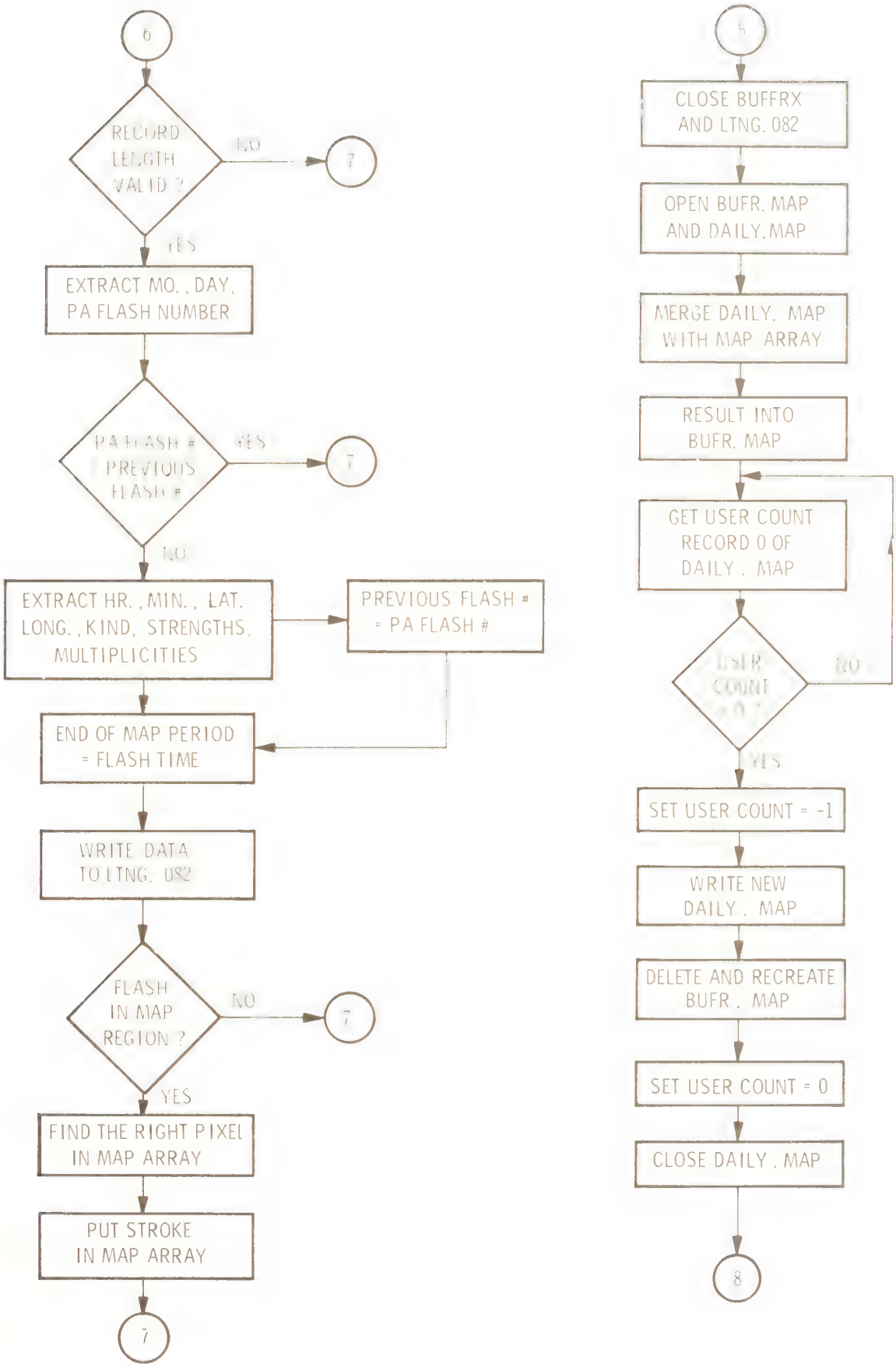
OUR NETWORK


LOCAL LTNG.
2- SYSTEM BOISE DATA
COLOR COMPUTER DISPLAY
COMPUCORP 625 DATA HANDLER/ MASSAGER & ARCHIVES
SUPERBRAIN ARCHIVER/ BACKUP FORMATTER
PERKIN – ELMER 3200 ARCHIVER/ FORMATTER
TO USERS VIA DIAL – UP
REGION 1 BLM- STYLE READOUT H/. 9845

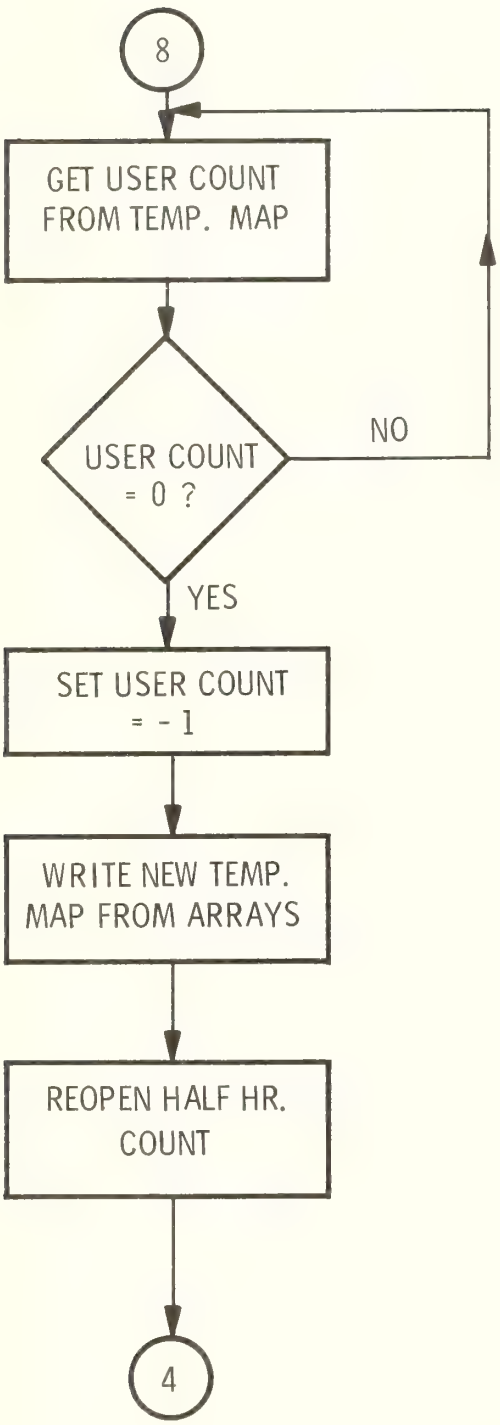
PERIODIC . BAS
(Page 1)

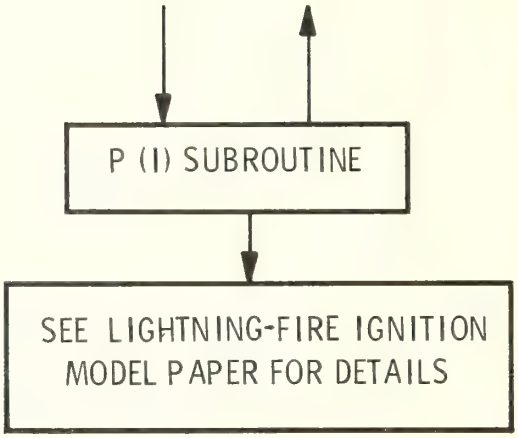

ENTRY
INITIALIZE, OPEN HALF HR. CNT. . SET COUNTS TO 1
4
GET CURRENT TIME IN MINUTES, FROM START OF YEAR
BEGIN TIME = CURRENT TIME
STALL LOOP
GET CURRENT TIME
CURRENT − BEGIN < LIMIT ?
YES
NO
FLOP RECORD 0 IN HALF HR. CNT.
INITIALIZE : MAP ARRAY BAD RECORD EOF FLAG
GET RECORD 2 1 IN HALF HR. CNT.
CURRENT VALUE = LAST VALUE ?
YES
NO
CLOSE HALF HR. CNT.
LAST REC. 1 = CURRENT REC. 1
SET " NO NEW WEATHER " FLAG = TRUE
OPEN UWU . 082 READ RECORD COUNT
CURRENT = OLD ?
YES
NO
RESET " NO NEW WEATHER " FLAG = FALSE
OLD REC. COUNT = CURRENT REC.
GET LATEST UWS & UPDATE
NEXT PAGE


FROM PAGE 1
CLOSE UWU, OPEN AFFIRMS
GET CURRENT RECORD COUNT
CURRENT = OLD ?
YES
NO
RESET " NO NEW WEATHER FLAG "
OLD RECORD COUNT = NEW RECORD COUNT
GET AFFIRMS DATA
CLOSE AFFIRMS .082
NEW WEATHER ?
NO
3
YES
2
2
READ SQRDATA . DTA
P(I) SUBROUTINE (Page 4)
FIGURE P (I) FOR EACH PIXEL
3
OPEN BUFFER FILE TO READ
OPEN LTNG. 082 FOR WRITE
7
GET RECORD FROM BUFFRX
END OF BUFFER ?
YES
EOF = TRUE
NO
EOF = TRUE ?
YES
5
GO MAKE MAPS
NO
6
GO PROCESS A RECORD

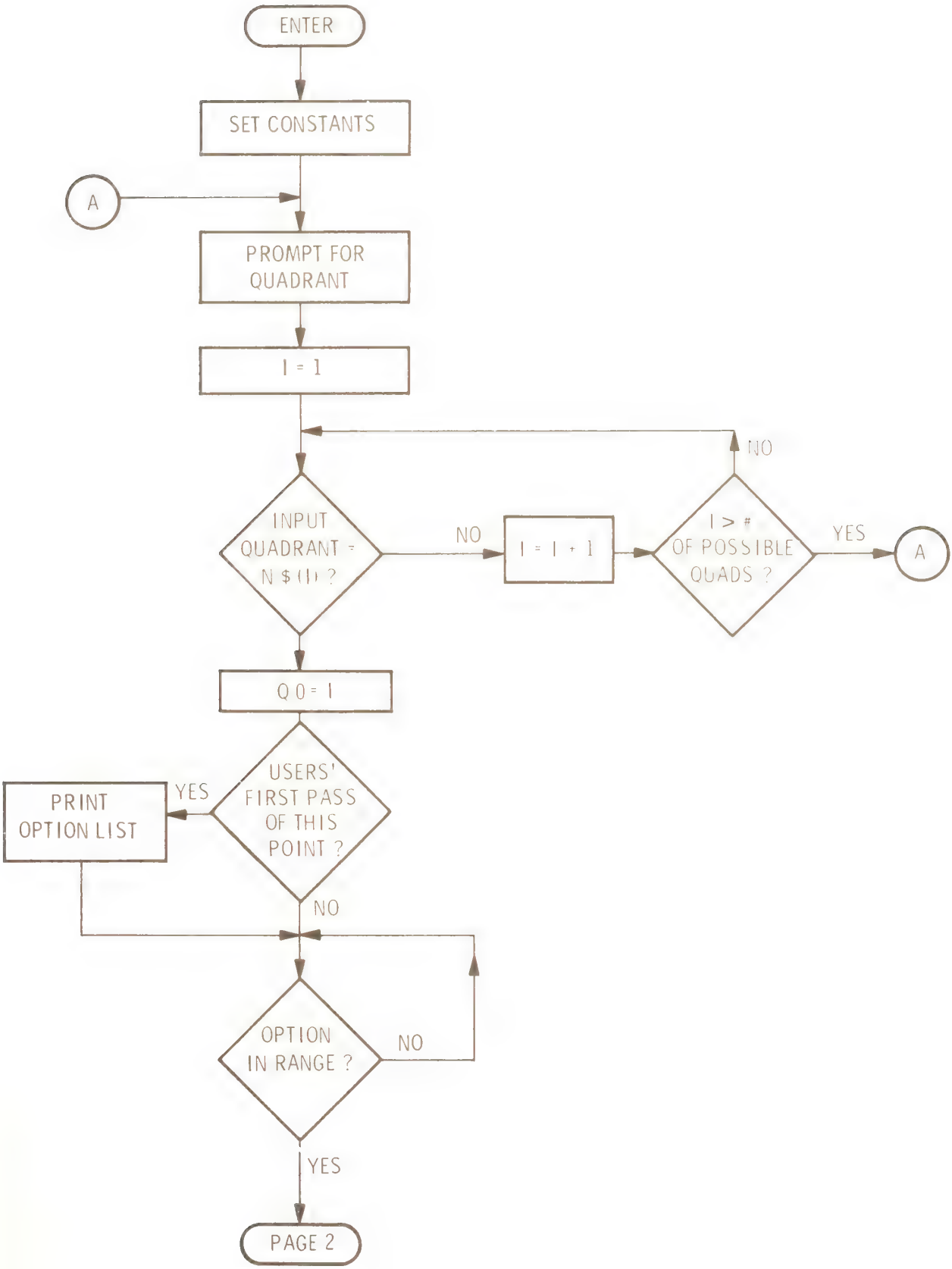

6
RECORD LENGTH VALID ?
NO
7
YES
EXTRACT MO., DAY, PA FLASH NUMBER
PA FLASH # = PREVIOUS FLASH #
YES
7
NO
EXTRACT HR., MIN., LAT. LONG., KIND, STRENGTHS, MULTIPLICITIES
PREVIOUS FLASH # = PA FLASH #
END OF MAP PERIOD = FLASH TIME
WRITE DATA TO LTNG. 082
FLASH IN MAP REGION ?
NO
7
YES
FIND THE RIGHT PIXEL IN MAP ARRAY
PUT STROKE IN MAP ARRAY
7
5
CLOSE BUFFRX AND LTNG. 082
OPEN BUFR. MAP AND DAILY. MAP
MERGE DAILY. MAP WITH MAP ARRAY
RESULT INTO BUFR. MAP
GET USER COUNT RECORD 0 OF DAILY . MAP
USER COUNT = 0 ?
NO
YES
SET USER COUNT = -1
WRITE NEW DAILY . MAP
DELETE AND RECREATE BUFR . MAP
SET USER COUNT = 0
CLOSE DAILY . MAP
8

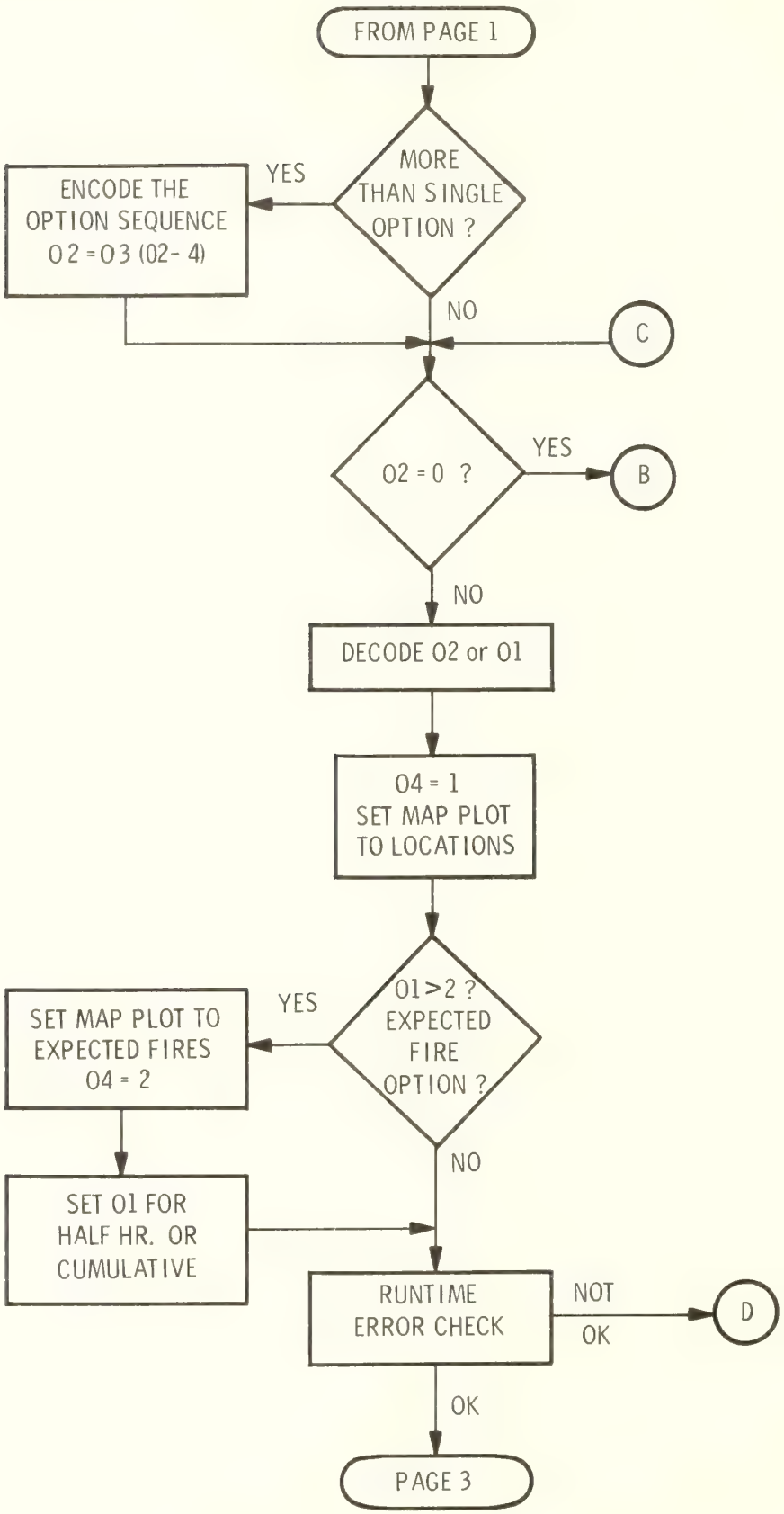
PERIODIC . BAS
(Page 4)

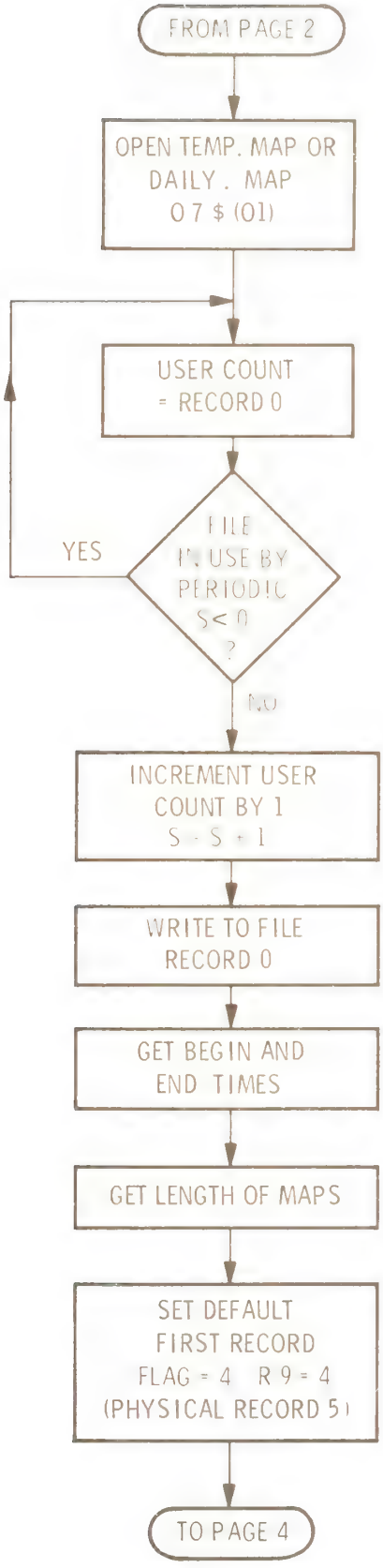




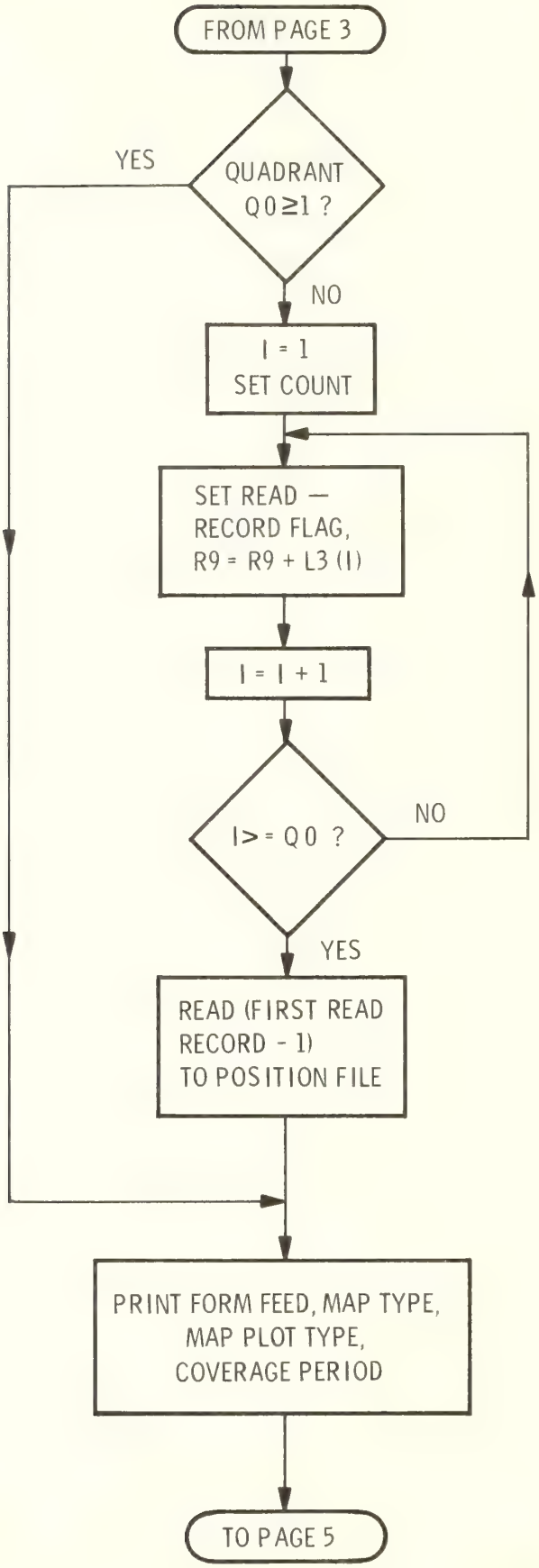
SHOWTIME . BAS
(Page 1)



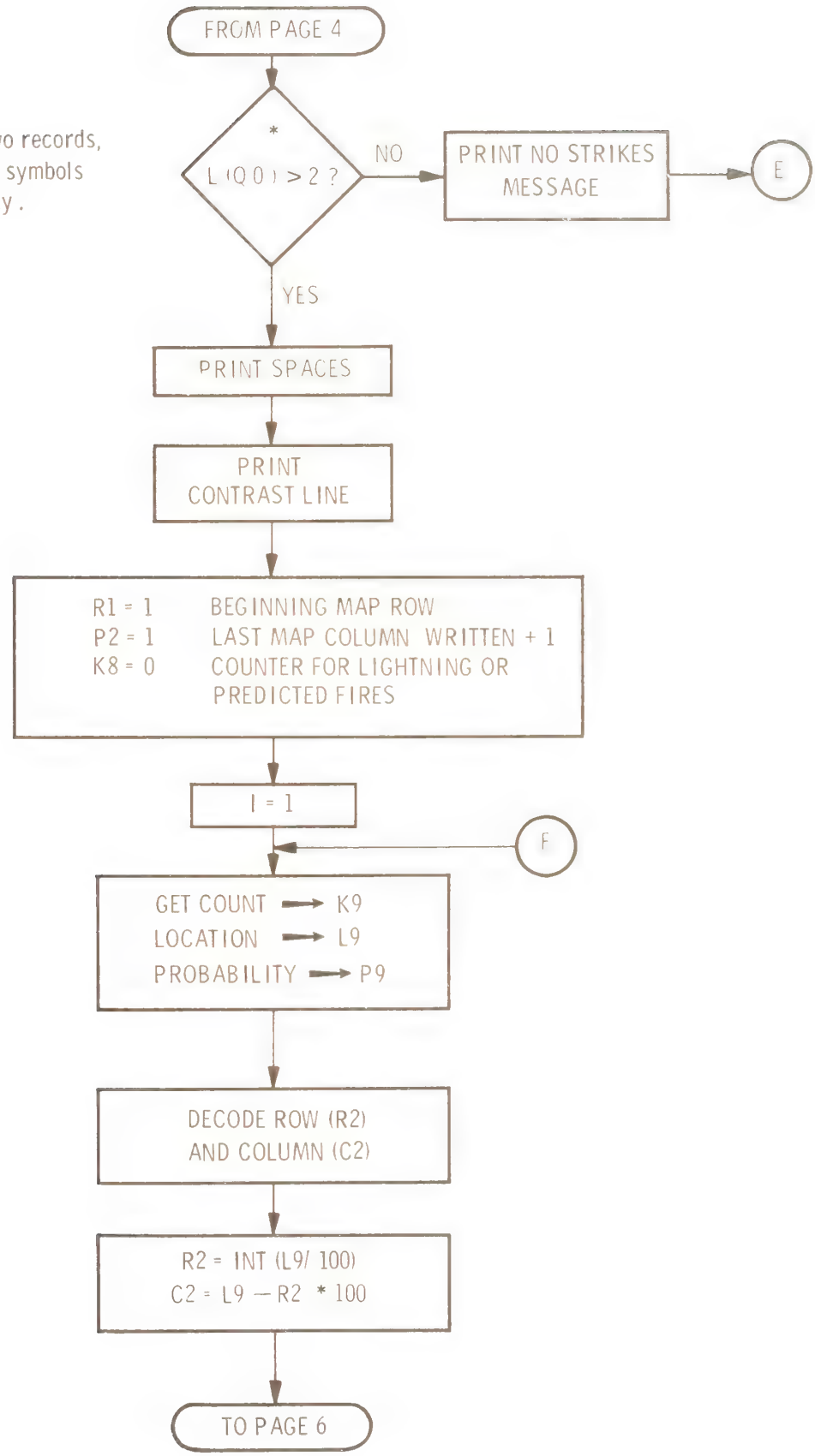

FROM PAGE 1
MORE THAN SINGLE OPTION ?
YES
ENCODE THE OPTION SEQUENCE O2 = O3 (O2 - 4)
NO
C
O2 = 0 ?
YES
B
NO
DECODE O2 or O1
O4 = 1
SET MAP PLOT TO LOCATIONS
O1 > 2 ? EXPECTED FIRE OPTION ?
YES
SET MAP PLOT TO EXPECTED FIRES O4 = 2
NO
SET O1 FOR HALF HR. OR CUMULATIVE
RUNTIME ERROR CHECK
NOT OK
D
OK
PAGE 3


FROM PAGE 2
OPEN TEMP. MAP OR
DAILY . MAP
0 7 $ (01)
USER COUNT
= RECORD 0
FILE
IN USE BY
PERIODIC
S< 0
?
YES
NO
INCREMENT USER
COUNT BY 1
S - S + 1
WRITE TO FILE
RECORD 0
GET BEGIN AND
END TIMES
GET LENGTH OF MAPS
SET DEFAULT
FIRST RECORD
FLAG = 4 R 9 = 4
(PHYSICAL RECORD 5)
TO PAGE 4

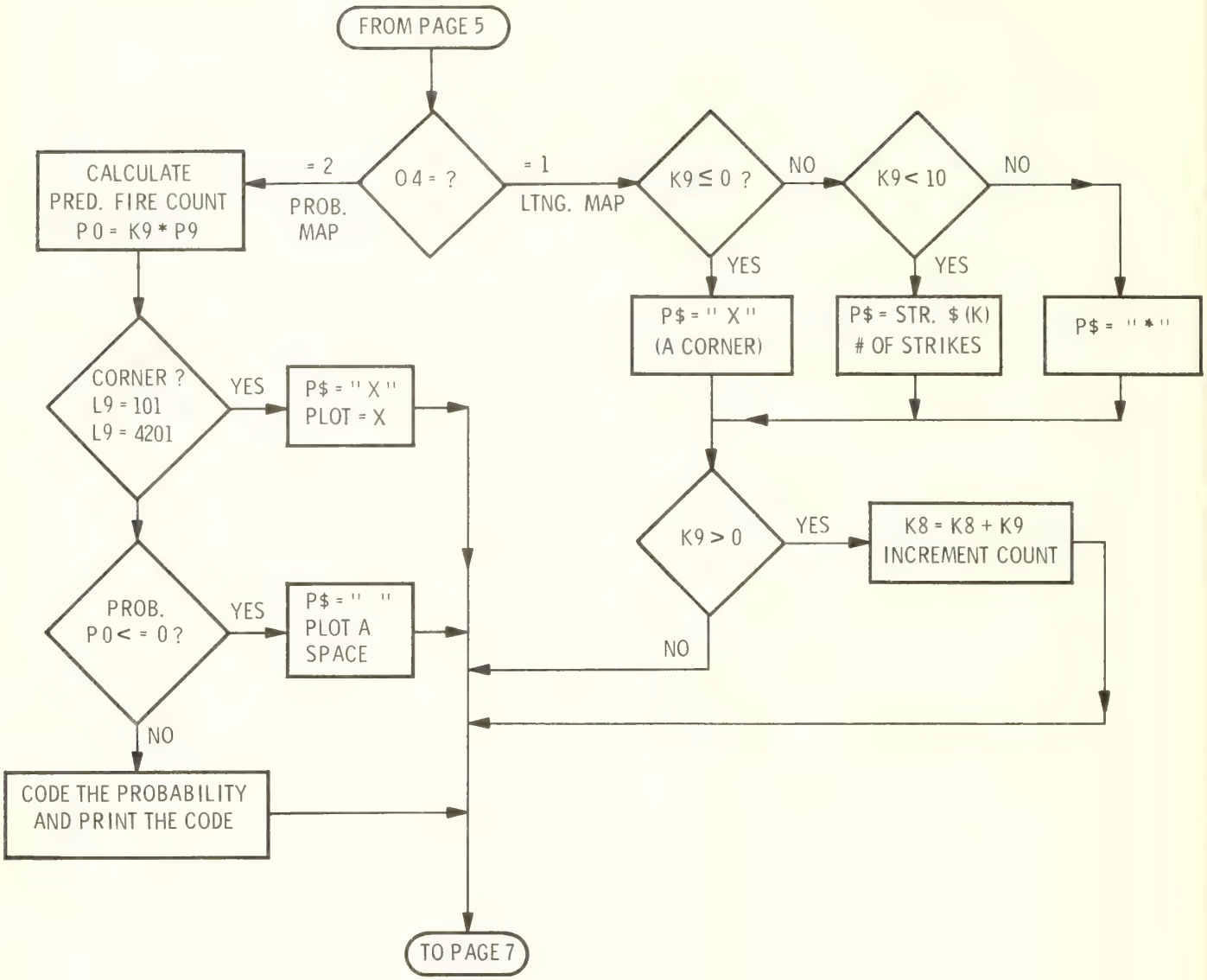
SHOWTIME . BAS
(Page 4)


FROM PAGE 3
QUADRANT Q0≥1 ?
YES
NO
I = 1
SET COUNT
SET READ — RECORD FLAG, R9 = R9 + L3 (I)
I = I + 1
I>= Q0 ?
NO
YES
READ (FIRST READ RECORD - 1) TO POSITION FILE
PRINT FORM FEED, MAP TYPE, MAP PLOT TYPE, COVERAGE PERIOD
TO PAGE 5

* NOTE : If a map has only two records, they are the corner symbols and the map is empty .

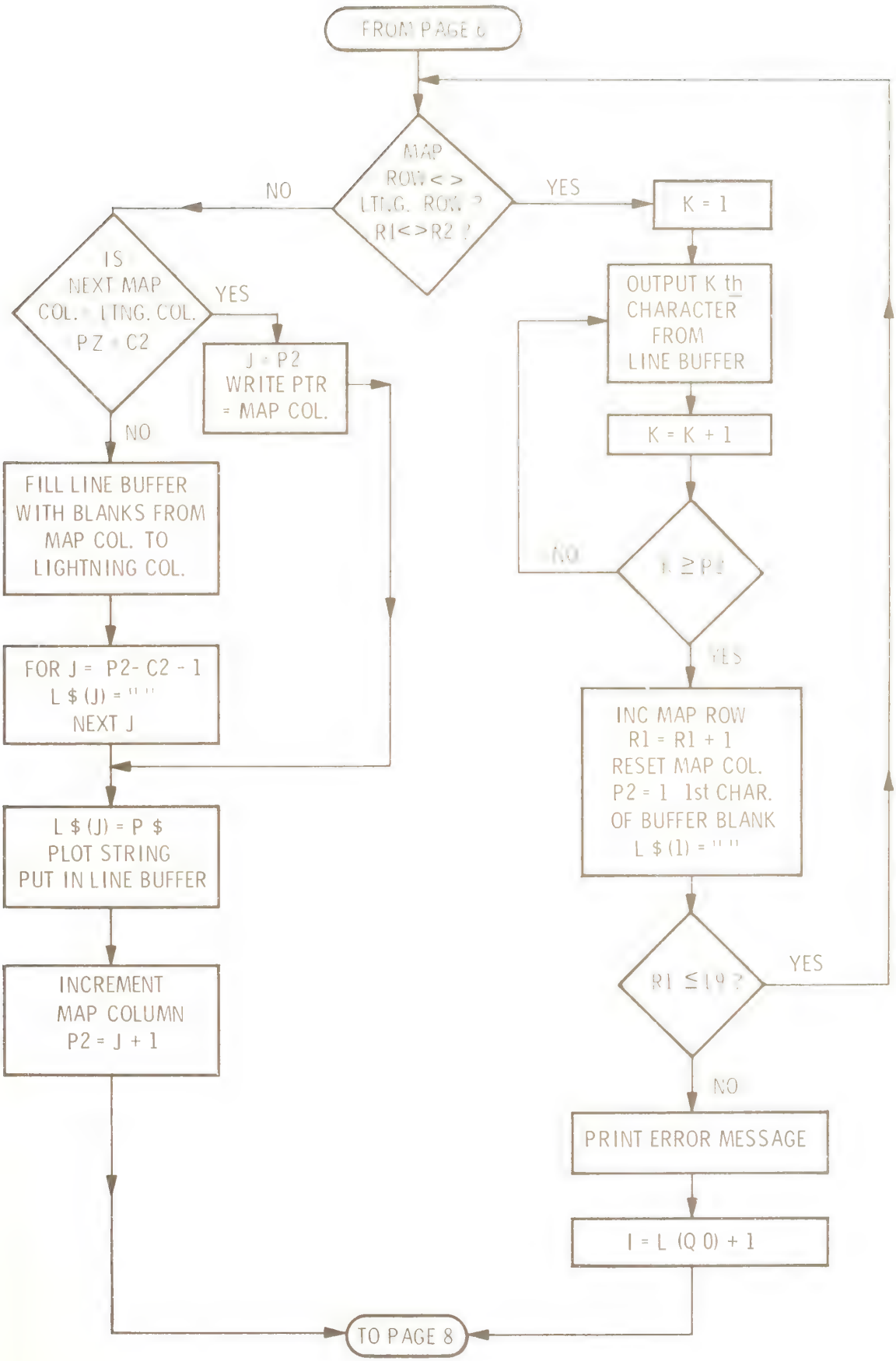

FROM PAGE 4
* L(Q 0) > 2 ?
NO
PRINT NO STRIKES MESSAGE
E
YES
PRINT SPACES
PRINT CONTRAST LINE
R1 = 1 BEGINNING MAP ROW
P2 = 1 LAST MAP COLUMN WRITTEN + 1
K8 = 0 COUNTER FOR LIGHTNING OR PREDICTED FIRES
I = 1
F
GET COUNT → K9
LOCATION → L9
PROBABILITY → P9
DECODE ROW (R2) AND COLUMN (C2)
R2 = INT (L9/ 100)
C2 = L9 — R2 * 100
TO PAGE 6

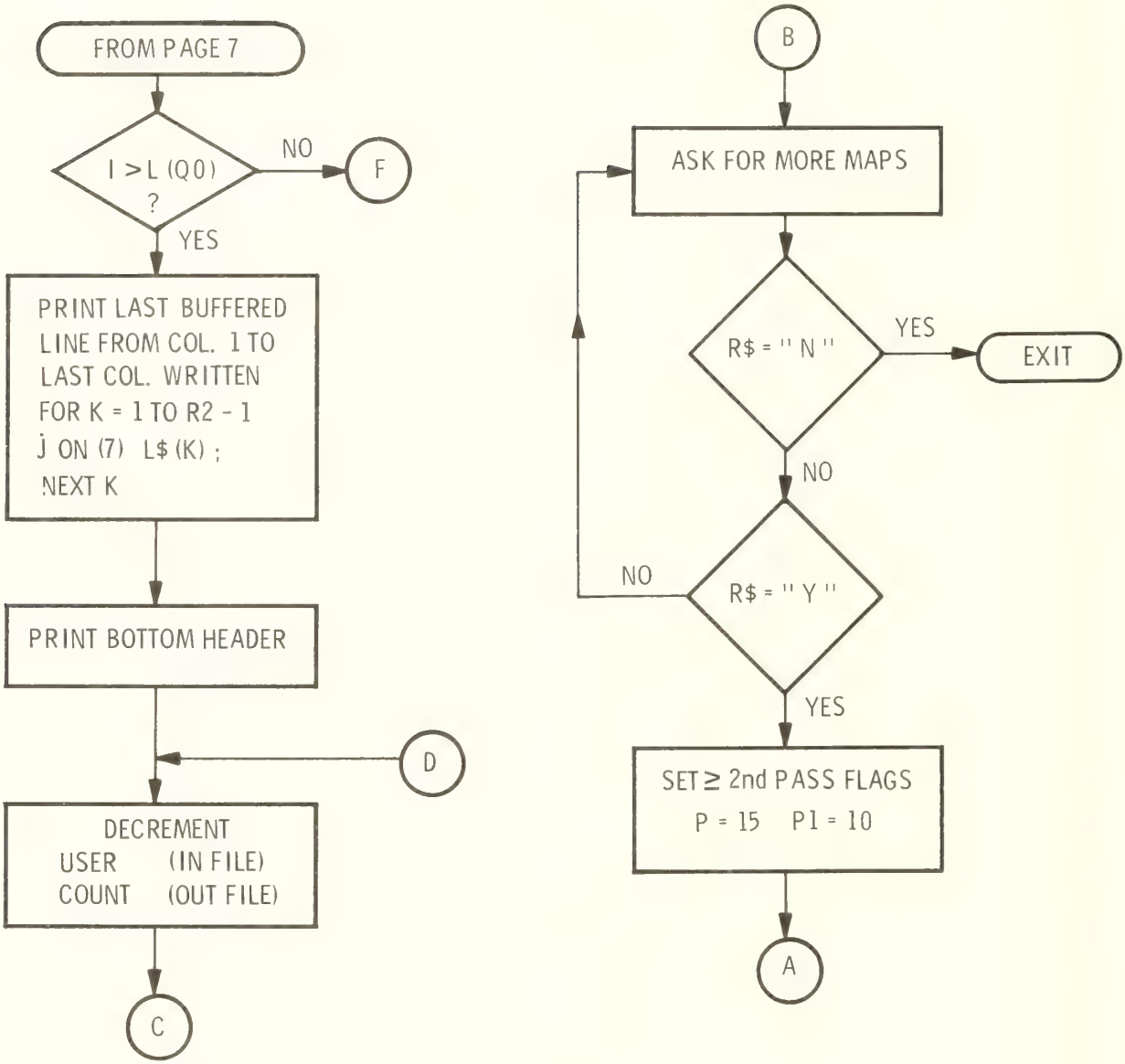
SHOWTIME . BAS
(Page 6)



SHOWTIME . BAS

(Page 7)


FROM PAGE 6
MAP ROW < > LTNG. ROW ? R1 < > R2 ?
NO
YES
K = 1
IS NEXT MAP COL. = LTNG. COL. P2 = C2
YES
J = P2 WRITE PTR = MAP COL.
NO
FILL LINE BUFFER WITH BLANKS FROM MAP COL. TO LIGHTNING COL.
FOR J = P2- C2 - 1 L $ (J) = " " NEXT J
L $ (J) = P $ PLOT STRING PUT IN LINE BUFFER
INCREMENT MAP COLUMN P2 = J + 1
OUTPUT K th CHARACTER FROM LINE BUFFER
K = K + 1
NO
YES
INC MAP ROW R1 = R1 + 1 RESET MAP COL. P2 = 1 1st CHAR. OF BUFFER BLANK L $ (1) = " "
R1 ≤ 19 ?
YES
NO
PRINT ERROR MESSAGE
I = L (Q 0) + 1
TO PAGE 8


FROM PAGE 7
I >L (Q0) ?
NO
F
YES
PRINT LAST BUFFERED LINE FROM COL. 1 TO LAST COL. WRITTEN
FOR K = 1 TO R2 - 1
J ON (7) L$ (K) ;
NEXT K
PRINT BOTTOM HEADER
D
DECREMENT
USER (IN FILE)
COUNT (OUT FILE)
C
B
ASK FOR MORE MAPS
R$ = " N "
YES
EXIT
NO
R$ = " Y "
NO
YES
SET ≥ 2nd PASS FLAGS
P = 15 P1 = 10
A

```
##########################################################################

 THIS IS THE SET OF PROGRAMS FOR LLAFFS WRITTEN ON/FOR THE PERKIN-
 ELMER 3200 IN BASIC. THE ABBREVIATION ; IS USED FOR PRINT AT TIMES
 IN THESE PROGRAMS. ALL OTHER FUNCTIONS ARE SPELLED OUT.

##########################################################################
 REM PROGRAM SQRFIL.BAS -- CREATES AND FILLS THE FILE SQRDATA.DTA
 REM  THE FILE CAN BE GIVEN A NAME OTHER THAN 'SQRDATA.DTA'
 DIM F$(12),E$(5)
 REM ************************************************************
 REM PROMPT THE USER
 REM
 ONERROR GOTO 80
 PRINT"NUMBER OF SQUARES YOUR AREA IS SECTIONED INTO ?"
 INPUT S0
 ONERROR GOTO 110
 PRINT"NAME FOR THE DATA FILE ?  (TYPE 'D' FOR DEFAULT='SQRDATA.DTA')"
 INPUT F$
 IF F$="D" THEN F$="SQRDATA.DTA"
 REM ************************************************************
 REM  CREATE  AND OPEN  FILE
 REM
 ONERROR GOTO 210
 CREATE F$,2,4
 OPEN F$,1,1
 GOTO 350
 E$=ERR$(0):E=VAL(E$)
 IF E=10 THEN ;"ILLEGAL FILE NAME.":GOTO 100
 IF E<>22 THEN ;"ERR NO."; E ;"AT LINE NO"; ERL(0):STOP
 PRINT"FILE "; F$ ;" ALREADY EXISTS."
 PRINT"TO DELETE "; F$ ;"  THEN  RECREATE  IT, TYPE 1"
 PRINT"TO STOP TYPE 0, TO TRY A NEW NAME, TYPE 2"
 ONERROR GOTO 240
 INPUT O1
 IF O1=0 THEN STOP
 IF O1=1 THEN DELETE F$:GOTO 170
 GOTO 100
 REM ************************************************************
 REM  FILL THE FILE
 REM
 FOR I=1 TO S0
 ONERROR GOTO 370
 PRINT"SQUARE NO."; I;"WEATHER STATION NBR.= "
 INPUT W0
 ONERROR GOTO 400
 PRINT"SQR NO."; I ;"FUEL TYPE INDEX.="
 INPUT F0
 W0=W0*100+F0
```

```
430 OUTFILE ON(1)W0
440 NEXTI
450 CLOSE1
460 PRINT F$ ;" FILLED AND CLOSED."
470 END
*************************************************************************
  AFFIRMS UPDATING PROGRAM
THIS PROGRAM USES THE FILE AFFIRMS.082 (OR OTHER YEAR)
WHICH MUST BE EXTERNALLY CREATED AT IMPLEMENTATION.
*************************************************************************
10    REM AFFIRMS.BAS -- AFFIRMS.YYY FILE UPDATER
20    CLOSE5:OPEN "CON:",5,0
30    DIM A(73),S0$(1),Y$(4),F$(12)
40    PRINT ON(5)"PROGRAM AFFIRMS//ENTER YEAR OF DATA (2 DIGITS)":INPUT ON(5)Y$
50    F$="AFFIRMS.0"+Y$
60    CLOSE1:OPEN F$,1,0:INFILE ON(1,0)Z,Z1
70    PRINT ON(5)"REWRITE (R)  OR  APPEND(A) ?":INPUT ON(5)S0$
80    IF S0$="R" THEN Z=0 ELSE IF S0$<>"A" GOTO 70
90    IF Z<1 THEN  PRINT ON(5)"WARNING -- IN REWRITE MODE."
100   PRINT ON(5)"ENTER 0 TO STOP , ANY OTHER NUMBER TO CONTINUE."
110   ONERROR GOTO 100
120   INPUT ON(5)S0
130   IF S0=0 THEN STOP
140   PRINT ON(5)"ENTER MO,DAY,HR OF MEAS. (1 OR 2 DIGITS)":INPUT ON(5)M,D,H
150   T=(M-1)*44640+D*1440+H*60
160   ONERROR GOTO 210
170   FOR I=1 TO 73
180   PRINT ON(5)"ENTER STATION NO.  " ; I
190   PRINT ON(5)"LAL=":INPUT ON(5)L
200   PRINT ON(5)"FMI=":INPUT ON(5)F: GOTO 220
210   PRINT ON(5)CHR$(7) ;"ERROR": GOTO 180
220   A(I)=L*100+F
230   NEXTI
240   ONERROR GOTO 370
250   REM (* APPEND NEW DATA TO END OF FILE *)
260   OUTFILE ON(1,Z+1)T,A(1),A(2),A(3),A(4),A(5),A(6),A(7),A(8)
270   OUTFILE ON(1)A(9),A(10),A(11),A(12),A(13),A(14),A(15),A(16),A(17)
280   OUTFILE ON(1)A(18),A(19),A(20),A(21),A(22),A(23),A(24),A(25),A(26)
290   OUTFILE ON(1)A(27),A(28),A(29),A(30),A(31),A(32),A(33),A(34),A(35)
300   OUTFILE ON(1)A(36),A(37),A(38),A(39),A(40),A(41),A(42),A(43),A(44)
310   OUTFILE ON(1)A(45),A(46),A(47),A(48),A(49),A(50),A(51),A(52),A(53)
320   OUTFILE ON(1)A(54),A(55),A(56),A(57),A(58),A(59),A(60),A(61),A(62)
330   OUTFILE ON(1)A(63),A(64),A(65),A(66),A(67),A(68),A(69),A(70),A(71)
340   OUTFILE ON(1)A(72),A(73)
350   Z=Z+9:OUTFILE ON(1,0)Z,Z1
360   CLOSE1: PRINT ON(5)"DATE " ; T ;" APPENDED TO FILE " ; F$:STOP
370   PRINT ON(5)"ERROR" ; ERR$(165) ;"  LINE" ; ERL(0)
380   END
*************************************************************************
```

```
   UPPER WIND SPEED UPDATE PROGRAM
   THIS PROGRAM USES THE FILE UWU.082 (OR OTHER YEAR)
   WHICH MUST BE EXTERNALLY CREATED AT IMPLEMENTATION.
*******************************************************************************
10    REM UWU.BAS -- UPPER WIND SPEED FILE (UWU.YYY) UPDATER
20    CLOSE5:OPEN"CON:",5,0
30    DIM W(4),G(3,3),C(3),S(3)
40    DIM Y$(4),S0$(1),F$(12),C$(12)
50    PRINT ON(5)"PROGRAM UWU"
60    PRINT ON(5)"YEAR PRESENTLY SET FOR 1982":Y$="82"
70    F$="UWU.0"+Y$
80    CLOSE1:OPENF$,1,0:INFILE ON(1,0)Z1
90    PRINT ON(5)"REWRITE (R)  OR  APPEND (A) ? "
100   INPUT  ON(5)S0$
110   IF S0$="R" THEN Z1=0 ELSE IF S0$<>"A" GOTO 90
120   IF Z1<1 THEN PRINT ON(5)"WARNING -- IN REWRITE MODE.": GOTO 150
130   INFILE ON(1,Z1)U,H(1),H(2),H(3)
140   PRINT"LAST UWU RECORD IS " ; U ; H(1) ; H(2) ; H(3)
150   PRINT"ENTER 0 TO STOP, ANY NUMBER TO RESUME UWU-RUN"
160   INPUT  ON(5)I
170   IF I=0 THEN STOP
180   PRINT ON(5)"ENTER 500MB WIND SPD FOR BOISE":INPUT  ON(5)W(1)
190   PRINT ON(5)"ENTER 500MB WIND SPD FOR SPOKANE":INPUT  ON(5)W(2)
200   PRINT ON(5)"ENTER 500MB WIND SPD FOR GRTFALLS":INPUT  ON(5)W(3)
210   PRINT ON(5)"ENTER MO,DAY,HR OF MEAS. (1 OR 2 DIGITS)"
220   INPUT  ON(5)M,D,H
230   T=(M-1)*44640+D*1440+H*60
240   OUTFILE ON(1,Z1+1)T,W(1),W(2),W(3)
250   Z1=Z1+1:OUTFILE ON(1,0)Z1
260   CLOSE1: PRINT ON(5)T;W(1);W(2);W(3);"APPENDED TO ";F$;" FOR ";M;D;H
270   END
*******************************************************************************
  MONITOR PROGRAM
        MONITOR USES SEVERAL FILES. THESE ARE SPECIFIC TO
        THE APPLICATION, EXCEPT FOR BUFFR1.LTG AND BUFFR2.LTG.
        THESE TWO ARE REQUIRED FOR PERIODIC.BAS. ALL FILES IN
        MONITOR MUST BE EXTERNALLY CREATED AT IMPLEMENTATION.
*******************************************************************************
10    CLOSE 7:OPEN "CON:",7,0
20    REM *****  PROGRAM SUPERMON
30    DIM  L$(80),K1$(1),R0$(80),F$(12),Y$(2),M1$(2),D1$(2),X$(1),E$(5)
40    DIM  A9$(1),N9$(1),D2$(1),C1$(1),C2$(1),C3$(1),C4$(1),C5$(1)
50    DIM  B$(10,2),A(73)
60    REM
70    D2$=CHR$(18):C1$=CHR$(1):C2$=CHR$(2):C3$=CHR$(3):C4$=CHR$(4)
80    C5$=CHR$(5):A9$=CHR$(6):N9$=CHR$(21):F=1:U1=1
90    I1=1:I2=2:S1=1
100   B$(1)="BUFFR1.LTG":B$(2)="BUFFR2.LTG"
110   PRINT ON(7)D2$; C2$
```

```
120  ONERROR GOTO 710
130  REM ************************************************************
140  OPEN "HALFHR.CNT",4,0
150  OPEN "VERBOSE.BOI",2,1:OPEN "BUFFR1.LTG",1,1
160   GOTO 250
170  REM *** CHECK FOR  END OF HALF HOUR PERIOD *********************
180  INFILE ON(4,0)S0
190  IF  S0=S1  THEN  RETURN
200  CLOSE U1:F=F+S1:S1=S0
210  OPEN B$(F),U1,1
220  OUTFILE ON(4,1)S1
230  RETURN
240  REM ***** WAIT FOR  INPUT  ON(7) FROM COMPUCORP
250  LINPUT ON(7)B0$
260  X$=B0$(I1,I1):L$=B0$(I2,):T0=ASC(X$)
270  ONT0 GOTO 300,330,470,360
280  PRINT ON(7)D2$; C5$;"PF:INVALID COMMAND": GOTO  250
290  REM..... OUR LTNG INFO HANDLER ......
300  OUTFILE ON(U1)L$
305  GOSUB  180
310  GOTO 250
320  REM..... BOISE LTNG INFO HANDLER ......
330  OUTFILE ON(2)L$
340  GOTO 250
350  REM ..... UPPER WIND HANDLER ......
360  GOSUB 680
370  F$="UWU.0"+Y$:CLOSE 5:OPEN F$,5,0:INFILE ON(5,0)Z,Z1
380  IF Z=Z1 THEN PRINT ON(7)N9$: GOTO 250
390  PRINT ON(7)A9$
400  Z1=Z1+1
410  INFILE ON(5,Z1)A(1),A(2),A(3)
420  FOR I=1TO3:PRINT ON(7)A(I):NEXTI
430  INPUT ON(7)K1$:  IF K1$<>A9$ GOTO 420
440  IF Z=Z1 THEN PRINT ON(7)C3$ ELSE PRINT ON(7)C4$: GOTO 400
450  OUTFILE ON(5,0)Z,Z1:CLOSE 5: GOTO 250
460  REM..... READ LATEST AFFIRMS DATA AND PASS TO COMPUCORP ......
470  GOSUB  680
480  F$="AFFIRMS.0"+Y$:CLOSE 5:OPEN F$,5,0:INFILE ON(5,0)Z,Z1
490  IF Z=Z1 THEN PRINT ON(7)N9$: GOTO 250
500  PRINT ON(7)A9$
510  Z1=Z1+9
520  INFILE ON(5,Z-8)T,A(1),A(2),A(3),A(4),A(5),A(6),A(7),A(8)
530  INFILE ON(5)A(9),A(10),A(11),A(12),A(13),A(14),A(15),A(16),A(17)
540  INFILE ON(5)A(18),A(19),A(20),A(21),A(22),A(23),A(24),A(25),A(26)
550  INFILE ON(5)A(27),A(28),A(29),A(30),A(31),A(32),A(33),A(34),A(35)
560  INFILE ON(5)A(36),A(37),A(38),A(39),A(40),A(41),A(42),A(43),A(44)
570  INFILE ON(5)A(45),A(46),A(47),A(48),A(49),A(50),A(51),A(52),A(53)
580  INFILE ON(5)A(54),A(55),A(56),A(57),A(58),A(59),A(60),A(61),A(62)
590  INFILE ON(5)A(63),A(64),A(65),A(66),A(67),A(68),A(69),A(70),A(71)
```

```
600   INFILE ON(5)A(72),A(73)
610   PRINT ON(7)T
620   FOR I=1 TO 73:PRINT ON(7)A(I):NEXTI
630   INPUT ON(7)K1$:  IF K1$<>A9$ THEN :"BAD BLK": GOTO 610
640   IF Z=Z1 THEN PRINT ON(7)C3$ ELSE PRINT ON(7)C4$: GOTO 510
650   OUTFILE ON(5,0)Z,Z1:CLOSE 5
660   GOTO 250
670   REM ..... GET DATE .....
680   D$=GETDATE$(0)
690   Y$=D$(7,8):M1$=D$(1,2):D1$=D$(4,5):RETURN
700   REM..... ERROR HANDLER .....
710   E$=ERR$(0):E=VAL(E$)
720   PRINT ON(7)D2$;C5$;:PRINT ON(7)"ERROR NO -";E;" AT LINE NO. ";ERL(0)
730   STOP
740   END
*****************************************************************************
  PERIODIC.....THE FILEMAKER AND PROBABILITY PROGRAM
       PERIODIC USES SEVERAL FILES. ALL MUST BE CREATED AT THE
       TIME OF IMPLEMENTATION. THE FILES ARE: HALFHR.CNT,
       LTOTL.DTA, TEMP.MAP,BUFR.MAP, BUFFR1.LTG, BUFFR2.LTG,
      LTNG.082, AND DAILY.MAP. LTNG.082 IS THE DATA ARCHIVE, AND MAY
      NOT BE NECESSARY FOR SOME USERS.
*****************************************************************************
10    REM PROGRAM PERIODIC
20    REM FLOPS THE STATE OF RECORD NBR. 0 IN THE FILE 'HALFHR.CNT'
30    REM EVERY HALF HOUR. MAKES THE MAP 'TEMP.MAP' FOR  SHOWTIME USERS.
40    DIM R$(10,2),K$(2),M1$(2),D$(2),H$(2),M2$(2),I$(80),C9(576)
50    DIM P$(4),T8$(2,4),T9$(2,4),SA$(6),S7$(6),M8$(1),M7$(2)
60    DIM L0(1000),K0(1000),L3(4),M9$(1,2),S8(2),L1$(6),L2$(7)
70    DIM D1$(8),T$(8),D9$(2),N9$(4),F1$(9),F2$(8),L5(4)
80    DIM S(6),S9(6),S3(6),S4(6),A(73),P(576),P9(1000),G(6)
90    REM ******************************************************
100   S(1)=2.856:S(2)=3.372:S(3)=3.896:S(4)=4.944:S(5)=7.04:S(6)=3.896
110   S9(1)=6.856:S9(2)=7.372:S9(3)=7.89                :S9(4)=8.944:S9(5)=11.04
120   S3(1)=-86.83:S3(2)=14                              .83:S3(4)=201.13:S3(5)=231.29
130   S3(6)=17                                           6)=7.896
140   A0=170                                             4293:Z8=.2
150   S4(1)=                                             )=7:S4(6)=8
160   S1=1:M                                             17:Y=49:N7=0:N8=0
170   R$(1)='                                            ":F2$="BUFR.MAP"
180   L9=47:R                                            :6
190   S2=1:C1
200   G(1)=0:                                             10000
210   FOR I=1
220   FOR I=1
230   REM ****                                            ********************
240   OPEN"HAL
250   OUTFILE
260   REM ****                                            ************
```

```
270   GOSUB 480
280   T9=T0
290   REM ***********************************************
300   FOR I=1 TO 1500:Q=0:NEXTI
310   GOSUB 480
320   IF T0-T9<T3 GOTO 300
330   S1=S1*M1:OUTFILE ON(1,0)S1: GOTO 560
340   REM ***********************************************
350   G1=1
360   IF Z<=G(G1) THEN RETURN
370   IF G1=5 THEN RETURN ELSE G1=G1+1
380   GOTO 360
390   REM ***************************************************************
400   GOSUB 480
410   T1=T0
420   INFILE ON(X3,0)S
430   IF S=Z0 THEN OUTFILE ON(X3,0)M1:RETURN
440   GOSUB 480
450   IF T0-T1>3 THEN OUTFILE ON(X3,0)M1 ELSE 420
460   RETURN
470   REM ***************************************************
480   D1$=GETDATE$(0):T$=GETTIME$(0)
490   D9$=D1$(1,2):M=VAL(D9$)
500   D9$=D1$(4,5):D=VAL(D9$)
510   D9$=T$(1,2):H=VAL(D9$)
520   D9$=T$(4,5):M2=VAL(D9$)
530   T0=(M-1)*44640+D*1440+H*60+M2
540   RETURN
550   REM ***********************************************************
560   L3(1)=2:L3(2)=Q0+2:L3(3)=2*Q0+2:L3(4)=3*Q0+2:P$="0000":F9=0
570   FOR I=0 TO 3:J=Q0*I+1
580   L0(J)=101:L0(J+1)=4201:K0(J)=-1:K0(J+1)=-1:P9(J)=0:P9(J+1)=0
590   NEXTI
600   GOTO 1130
610   REM ***********************************************
620   INFILE ON(1,1)S0
630   IF S0<>S2 THEN S2=S0:CLOSE1:RETURN
640   FOR I=1 TO 1500:D1=0:NEXTI
650   GOTO 620
660   REM ***********************************
670   OPEN"LTOTL.DTA",2,2
680   INFILE ON(2,0)C8
690   FOR I=1 TO 576:INFILE ON(2)C9(I),Z:NEXTI
700   CLOSE2
710   F=F+S2:OPENR$(F),2,2
720   OPEN"LTNG.082",3,1
730   RETURN
740   REM ***********************************
750   INFILE ON(2)L$
```

```
760   IF EOF(2) THEN F9=-1
770   RETURN
780   REM ************************************
790   IF LEN(L$)<>75 THEN RETURN
800   M1$=L$(1,2):D$=L$(3,4)
810   N9$=L$(5,8)
820   IF N9$=P$ THEN RETURN ELSE P$=N9$
830   H$=L$(10,11):M2$=L$(13,14)
840   L1$=L$(26,31):L6=VAL(L1$):L2$=L$(36,42):L7=VAL(L2$)
850   K$=L$(49,50)
860   L1$=L$(54,54):D9=VAL(L1$)
870   S8$=L$(57,62):M8$=L$(65,65):S7$=L$(67,72):M7$=L$(75,75)
880   S8(D9)=VAL(S8$):M9$(D9)=M8$
890   IF D9=C1 THEN D9=C2 ELSE D9=C1
900   S8(D9)=VAL(S7$):M9$(D9)=M7$
910   T9$(1)=M1$:T9$(2)=D$:T9$(3)=H$:T9$(4)=M2$
920   OUTFILE ON(3)L6,L7,S8(1),S8(2),M9$(1),M9$(2),K$,M1$,D$,H$,M2$
930   L1=L9-L6:L2=L8-L7
940   IF ABS(L1)>=R9 THEN RETURN
950   IF ABS(L2)>=R8 THEN RETURN
960   Y2=Y1*INT((Y-L6)*C6)
970   X1=Y2+INT((X-L7)*C4)+1
980   C9(X1)=C9(X1)+1
990   IF L1>=Z0 THEN Z=0 ELSE L1=C2+L1:Z=-2
1000  IF L2>=Z0 THEN Z=Z+C4 ELSE L2=C3+L2:Z=Z+3
1010  C0=INT(L2*24)+C1:R0=INT(L1*21)+C1
1020  B0=R0*100+C0
1030  K=(Q0*(Z-1))+C1
1040  IF (B0<=L0(K))OR(K>L3(Z)) GOTO 1060
1050  K=K+C1: GOTO 1040
1060  IF K>L3(Z) THEN L0(K)=B0:K0(K)=1:P9(K)=P(X1):L3(Z)=K:RETURN
1070  IF B0=L0(K) THEN K0(K)=K0(K)+C1:RETURN
1080  FOR I=L3(Z) TO KSTEP-1
1090  K0(I+1)=K0(I):L0(I+1)=L0(I):P9(I+1)=P9(I):NEXTI
1100  K0(K)=C1:L0(K)=B0:P9(K)=P(X1):L3(Z)=L3(Z)+1
1110  RETURN
1120  REM ******************************************************
1130  GOSUB 620
1140  GOSUB 1980
1150  GOSUB 670
1160  GOSUB 750
1170  IF F9 GOTO 1210
1180  GOSUB 790
1190  GOTO 1160
1200  REM ********************************************
1210  CLOSE2:CLOSE3
1220  OPEN"LTOTL.DTA",2,0
1230  INFILE ON(2,0)C8
1240  FOR I=1 TO 576:INFILE ON(2,I)Z,C8:OUTFILE ON(2,I)C9(I),C8:NEXTI
```

```
1250  CLOSE2
1260  OPEN F1$,2,0:OPEN F2$,3,1
1270  INFILE ON(2,3)L5(1),L5(2):INFILE ON(2,4)L5(3),L5(4)
1280  FOR I=1 TO 4
1290  K=(Q0*(I-1))+1:K1=L5(I)
1300  FOR J=1 TO K1
1310  INFILE ON(2)K4,L4,P4
1320  IF L0(K)<>L4 GOTO 1390
1330  K4=K4+K0(K)
1340  OUTFILE ON(3)K4,L4,P9(K)
1350  K=K+1
1360  IF K<=L3(I) GOTO 1500
1370  IF J=K1 GOTO 1500
1380  J2=J+1: GOTO 1450
1390  IF L0(K)<L4 GOTO 1410
1400  OUTFILE ON(3)K4,L4,P4: GOTO 1500
1410  OUTFILE ON(3)K0(K),L0(K),P9(K)
1420  K=K+1:L5(I)=L5(I)+1
1430  IF K<=L3(I) GOTO 1320
1440  IF J=K1 GOTO 1500 ELSE J2=J
1450  FOR J1=J2 TO K1
1460  INFILE ON(2)K4,L4,P4
1470  OUTFILE ON(3)K4,L4,P4
1480  NEXTJ1
1490  J=J1
1500  NEXTJ
1510  IF K>L3(I) GOTO 1560
1520  FOR J=K TO L3(I)
1530  OUTFILE ON(3)K0(J),L0(J),P9(J)
1540  L5(I)=L5(I)+1
1550  NEXTJ
1560  NEXTI
1570  CLOSE3:OPEN F2$,3,2
1580  X3=2:GOSUB 400
1590  OUTFILE ON(2,2)T9$(1),T9$(2),T9$(3),T9$(4)
1600  OUTFILE ON(2,3)L5(1),L5(2):OUTFILE ON(2,4)L5(3),L5(4)
1610  INFILE ON(3)K4,L4,P4
1620  IF EOF(3) GOTO 1650
1630  OUTFILE ON(2)K4,L4,P4
1640  GOTO 1610
1650  CLOSE3:DELETE F2$:CREATE F2$,2,12
1660  OUTFILE ON(2,0)Z0:CLOSE2
1670  REM ************************************************
1680  OPEN"TEMP.MAP",5,0
1690  X3=5:GOSUB 400
1700  OUTFILE ON(5,1)T8$(1),T8$(2),T8$(3),T8$(4)
1710  OUTFILE ON(5,2)T9$(1),T9$(2),T9$(3),T9$(4)
1720  FOR I=1 TO 4:L3(I)=L3(I)-(Q0*(I-1)):NEXTI
1730  OUTFILE ON(5,3)L3(1),L3(2)
```

```
1740  OUTFILE ON(5,4)L3(3),L3(4)
1750  FOR I=0 TO 3
1760  K=Q0*I
1770  FOR J=K+1 TO K+L3(I+1)
1780  OUTFILE ON(5)K0(J),L0(J),P9(J)
1790  NEXTJ
1800  NEXTI
1810  OUTFILE ON(5,0)Z0
1820  CLOSE5
1830  FOR I=1 TO 4:T8$(I)=T9$(I):NEXTI
1840  DELETE B$(F)
1850  CREATE B$(F),2,78
1860  OPEN"LTOTL.DTA",1,0
1870  INFILE ON(1,0)C8
1880  FOR I=1 TO 576
1890  INFILE ON(1)Z,Z1
1900  GOSUB 350
1910  IF G1<=Z1 THEN 1930
1920  OUTFILE ON(1,I)Z,G1:C8=-1
1930  C9(I)=G1
1940  NEXTI
1950  OUTFILE ON(1,0)C8:CLOSE1
1960  OPEN"HALFHR.CNT",1,0: GOTO 270
1970  REM ************************************************
1980  N9=-1
1990  OPEN"UWU.082",2,2:INFILE ON(2,0)Z,Z1
2000  IF Z=N7 GOTO 2030
2010  N9=0:N7=7:INFILE ON(2,N7)Z1,W1,W2,W3
2020  W=(W1+W2+W3)/3
2030  CLOSE2:OPEN"AFFIRMS.082",2,2:INFILE ON(2,0)Z,Z1
2040  IF Z=N8 GOTO 2150
2050  N9=0:N8=Z
2060  INFILE ON(2,Z-8)Z1,A(1),A(2),A(3),A(4),A(5),A(6),A(7),A(8)
2070  INFILE ON(2)A(9),A(10),A(11),A(12),A(13),A(14),A(15),A(16),A(17)
2080  INFILE ON(2)A(18),A(19),A(20),A(21),A(22),A(23),A(24),A(25),A(26)
2090  INFILE ON(2)A(27),A(28),A(29),A(30),A(31),A(32),A(33),A(34),A(35)
2100  INFILE ON(2)A(36),A(37),A(38),A(39),A(40),A(41),A(42),A(43),A(44)
2110  INFILE ON(2)A(45),A(46),A(47),A(48),A(49),A(50),A(51),A(52),A(53)
2120  INFILE ON(2)A(54),A(55),A(56),A(57),A(58),A(59),A(60),A(61),A(62)
2130  INFILE ON(2)A(63),A(64),A(65),A(66),A(67),A(68),A(69),A(70),A(71)
2140  INFILE ON(2)A(72),A(73)
2150  CLOSE2
2160  OPEN"LTOTL.DTA",2,0
2170  INFILE ON(2,0)C8:CLOSE2
2180  IF C8 THEN N9=0
2190  IF N9 THEN RETURN
2200  OPEN"SQRDATA.DTA",2,2
2210  FOR I=1 TO 576
2220  INFILE ON(2)P(I)
```

```
2230  GOSUB 2300
2240  P(I)=P0
2250  NEXTI
2260  CLOSE2
2270  RETURN
2280  REM ************************************************************************
2290  REM FIGURE PROBABILITY FOR  ONE SQUARE
2300  S7=INT(P(I)/100):R1=P(I)-S7*100
2310  R0=S4(R1)*.16E-1
2320  L=INT(A(S7)/100):F0=A(S7)-L*100
2330  IF L<>6 THEN L=C9(I)
2340  D0=-S(L)/W
2350  F5=0:F4=1
2360  IF L=6 GOTO 2420
2370  F5=(S3(L)*W*S(L)+C*S(L)*S(L))/(S3(L)*W*S9(L)+C*S9(L)*S9(L))
2380  F4=1-F5
2390  F3=F0+(Z6-F0)*(1-EXP(D0)):F3=F3/100
2400  E=R0*(A0+B*F3)
2410  P1=(1+(E/B9)^T8)^A9
2420  F3=F0/100
2430  E=R0*(A0+B*F3)
2440  P2=(1+(E/B9)^T8)^A9
2450  P0=(F5*P1+F4*P2)*Z8
2460  RETURN
2470  REM ************************************************************
2480  END
************************************************************************
 SHOWTIME ................ FORMATTING AND OUTPUT  PROGRAM
      ALL FILES IN SHOWTIME HAVE ALREADY BEEN CREATED IN IMPLEMENTING
      THE OTHER PROGRAMS.
************************************************************************
10    REM SHOWTIME
20    CLOSE7:OPEN"CON:",7,0
30    DIM N$(9,4),P$(1),Q$(8),L$(1,73),Q0$(2),N1$(2,4),L1$(73)
40    DIM M$(2),M1$(2),M2$(2),M3$(2),D$(2),D2$(2),H$(2),H2$(2),Q3$(25,2)
50    DIM R$(1),Q9$(39),Q8$(22),Q7$(9,2),Q3(3),Q6$(10,2),Q5$(70),Q4$(15,2)
60    N$(1)="NORTHWEST":N$(2)="NORTHEAST"
70    N$(3)="SOUTHWEST":N$(4)="SOUTHEAST"
80    Q9$="WHICH QUADRANT WOULD YOU LIKE  TO  SEE ?"
90    Q8$="ENTER AN OPTION NUMBER"
100   Q7$(1)="TEMP.MAP":Q7$(2)="DAILY.MAP"
110   Q6$(1)="HALF HOUR":Q6$(2)="CUMULATIVE"
120   Q5$="************************************************************"
130   Q4$(1)=" LIGHTNING ":Q4$(2)=" EXPECTED FIRE "
140   Q3$(1)=" STRIKES IN THE QUADRANT."
150   Q3$(2)=" SQUARES EXPECTING FIRES."
160   Q3(1)=21:Q3(2)=43:Q3(3)=42
170   N1$(1)="NW":N1$(2)="NE":N1$(3)="SW":N1$(4)="SE":P=38:P1=1:L8=43
180   REM ************************************************************
```

```
190   REM GET USER INPUT
200   ONERROR GOTO  210
210   PRINT ON(7)Q9$(1,P) :"  (NW,NE,SW,SE)"
220   INPUT  ON(7)Q0$
230   REM ************************************************************
240   I=1
250   IF Q0$=N1$(I) THEN Q0=I: GOTO  280
260   I=I+1:IF I>4 GOTO  210 ELSE 250
270   REM ************************************************************
280   IF P=15 THEN 410
290   PRINT ON(7): PRINT ON(7)"   OPTIONS"
300   PRINT ON(7)"     LIGHTNING MAPS"
310   PRINT ON(7)"      1. LAST HALF HOUR"
320   PRINT ON(7)"      2. CUMULATIVE"
330   PRINT ON(7)"     EXPECTED FIRE MAPS"
340   PRINT ON(7)"      3. LAST HALF HOUR"
350   PRINT ON(7)"      4. CUMULATIVE"
360   PRINT ON(7)"     OTHERS"
370   PRINT ON(7)"      5. 1 AND 2"
380   PRINT ON(7)"      6. 3 AND 4"
390   PRINT ON(7)"      7. 2 AND 4"
400   REM ************************************************************
410   ONERROR GOTO  420
420   PRINT ON(7)Q8$(P1)
430   INPUT  ON(7)O2
440   REM ************************************************************
450   IF O2<1 OR O2>7 THEN 420
460   IF O2>4 THEN O2=O3(O2-4)
470   IF O2=0 GOTO  960
480   O4=INT(O2/10):O1=O2-(O4*10):O2=O4:O4=1
490   IF O1>2 THEN O4=2:O1=O1-2
500   REM ************************************************************
510   ONERROR GOTO  920
520   REM ; REQUESTED MAP
530   CLOSE2:OPEN Q7$(O1),2,0
540   INFILE ON(2,0)S
550   IF S<0 GOTO  540 ELSE OUTFILE ON(2,0)S+1
560   INFILE ON(2)M$,D$,H$,M1$
570   INFILE ON(2)M2$,D2$,H2$,M3$
580   INFILE ON(2)L(1),L(2)
590   INFILE ON(2)L(3),L(4)
600   R9=4
610   IF Q0=1 GOTO  640
620   FOR I=1 TO Q0-1:R9=R9+L(I):NEXTI
630   INFILE ON(2,R9)K9,L9,P9
640   PRINT ON(7): PRINT ON(7)CHR$(12)
650   PRINT ON(7)"THIS IS THE " ; N$(Q0) ;" " ; Q6$(O1) ; Q4$(O4) ;"MAP."
660   PRINT ON(7)"THIS MAP COVERS THE PERIOD"
670   PRINT ON(7)"FROM :  ";M$;"/";D$;"    ";H$;":";M1$;"    (MDT)"
```

```
680   PRINT ON(7)" TO    :  ";M2$;"/";D2$;"    ";H2$;":";M3$;"    (MDT)"
690   IF L(Q0)>2 THEN 710 ELSE PRINT ON(7)
700   PRINT ON(7)"NO LIGHTNING IN THE " ; N$(Q0) ;" MAP AREA.": GOTO 910
710   PRINT ON(7)Q5$
720   PRINT ON(7)
730   REM ************************************************************
740   R1=1:P2=1:K8=0
750   FOR I=1 TO L(Q0)
760   INFILE ON(2)K9,L9,P9
770   R2=INT(L9/100):C2=L9-R2*100
780   ON04GOSUB 1010,1050
790   IF R1<>R2 THEN 830
800   IF P2=C2 THEN J=P2: GOTO  820
810   FOR J=P2 TO (C2-1):L$(J)=" ":NEXTJ
820   L$(J)=P$:P2=J+1: GOTO  870
830   FOR K=1 TO P2-1: PRINT ON(7)L$(K) ; :NEXTK: PRINT ON(7)
840   R1=R1+1:P2=1:L$(1)=" "
850   IF R1<=L8 GOTO  790
860   PRINT ON(7)"INTERNAL ERROR. UNABLE  TO  FINISH MAP.":I=L(Q0)+1
870   NEXTI
880   FOR K=1 TO P2-1: PRINT ON(7)L$(K) ; :NEXTK: PRINT ON(7)
890   PRINT ON(7)
900   PRINT ON(7)"THERE WERE " ; K8 ; Q3$(04)
910   PRINT ON(7)Q5$
920   INFILE ON(2,0)S:OUTFILE ON(2,0)S-1:CLOSE2
930   PRINT ON(7): PRINT ON(7)
940   GOTO  470
950   REM ****************************************************
960   PRINT ON(7)"MORE MAPS ?  (Y OR N)"
970   INPUT  ON(7)R$
980   IF R$="N" THEN STOP ELSE IF R$="Y" THEN P=15:P1=10: GOTO  200
990   GOTO  960
1000  REM ****************************************************
1010  IF K9<=0 THEN P$="X" ELSE IF K9<10 THEN P$=STR$(K9) ELSE P$="*"
1020  IF K9>0 THEN K8=K8+K9
1030  RETURN
1040  REM ************************************************************
1050  P0=K9*P9
1060  IF L9=1010RL9=4201 THEN P$="X":RETURN
1070  IF P0<=0 THEN P$=" ":RETURN
1080  K8=K8+1
1090  IF P0<=.2 THEN P$="1":RETURN
1100  IF P0<=.4 THEN P$="2":RETURN
1110  IF P0<=.8 THEN P$="3" ELSE P$="4"
1120  RETURN
1130  REM ****************************************************
1140  END
```

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Latham, Don. LLAFFS—a lightning-locating and fire-forecasting system. Res. Pap. INT-315. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 44 p.

This paper presents a system for locating lightning strikes and predicting the number of fire ignitions on forests and rangelands. This system uses variables representing weather and fuels and real-time lightning locations as inputs. Outputs from the system consist of printouts designed for use with overlays to map probable fire locations. The programs are designed to be used by field personnel having access to a micro- or minicomputer.

KEYWORDS: lightning, lightning location, ignition probability

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Variation in Production and Seasonal Development of Mountain Grasslands in Western Montana

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WALTER F. MUEGGLER spent 13 years investigating ecological relationships on mountain grasslands in western Montana. Dr. Mueggler is currently principal plant ecologist and leader of the Intermountain Station's Aspen Ecology and Management Research Work Unit at Logan, Utah.

RESEARCH SUMMARY

A 10-year study of mountain grasslands indicated that although total herbage production can differ as much as 200 percent between good and poor years, in 2 out of 3 years it can be expected to be within 85 to 90 percent of the long-term mean; production of forbs can vary as much as 250 percent between years, yet two-thirds of the time be within 80 to 85 percent of the long-term mean; total production of graminoids may differ as much as 275 percent between years, yet remain within 75 percent of their mean two-thirds of the time. Yearly variability in production of individual species is usually much greater. Weather-based models accounting for this production variability differ appreciably between nearby sites on different exposures. Although the greatest yearly difference in the beginning of growth in the spring for most species was from 25 to 30 days, in 2 out of 3 years the beginning of growth can be expected to be within 8 to 12 days of long-term means. The date of flowering of early-blooming species is twice as variable as that of late-blooming species. Yearly variation in start of seed dissemination was highly species dependent; the maximum difference between years ranged from 3 to 6 weeks. Two-thirds of the time seed dissemination can be expected to begin within 6 to 8 days and plant drying within 12 days of long-term means. Although growth and flowering began about 1 week later on northeast than on southwest exposures, no consistent difference existed between exposures in date of seed dissemination or in growth duration. Early growth appeared most closely associated with May and June temperatures. Vegetation readiness for grazing can differ as much as 5 weeks over a 10-year period, but can be expected to be within 2 weeks of the long-term mean in 2 out of 3 years.

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INTRODUCTION

The rate of plant development and the total amount of growth produced on native rangelands can vary greatly from year to year. These variations in development and yield are vital considerations in planning proper grazing management. In addition, knowledge of the growth of individual plant species as affected by yearly variations in weather is fundamental to understanding the dynamics of grassland ecosystems.

Despite the conspicuousness and importance of plant growth variations attributable to weather, these variations have been documented for few of the major range types in the West. Numerous workers have related total forage production to specific weather variables (Smoliak 1956; Johnston and others 1969; McLean and Smith 1973; Shiflet and Dietz 1974; Sneva 1977; Wight and Hanks 1981), but relatively few have attempted to describe the overall dynamics of range plant communities in relation to weather. Blaisdell's (1958) study of the sagebrush-grass range in southeastern Idaho is a notable example of such a comprehensive description of growth variations in plant communities.

Mountain grasslands are highly valued summer range for domestic livestock as well as for big-game animals in the mountainous West; this is particularly true in the Northern Rocky Mountains. To document the annual variation in plant development and herbage yield on a portion of this major range type, I conducted a study on both northerly and southerly exposures at two elevations on the Gravelly Range in southwestern Montana. Earlier I published the variations that occurred in plant growth over the initial 5-year period of this study and discussed the differences between elevations and exposures (Mueggler 1972a). A companion publication (Mueggler 1971) treats in detail variations in weather factors measured at the same locations and time. The study was continued for an additional 5 years on two exposures, but just at one elevation, to build a better data base for relating variations in weather to plant growth. The results of this 10-year study are reported here.

STUDY AREA

The two long-term study sites were near the north end of the Gravelly Range, approximately 12 miles (20 km) southwest of Virginia City in southwestern Montana. The sites were located on typical southwestern Montana mountain grasslands at 7,100 ft (2 164 m) elevation on opposing slopes approximately 590 ft (180 m) apart. One site was on a southwest exposure with 7-percent slope; the other was on a northeast exposure with 12-percent slope. Annual precipitation averaged approximately 20 inches (50 cm).

Soils of the area were derived from highly weathered residual limestone. The soil on the southwest exposure was a clayey-skeletal Calcic Cryoboroll with a 17-inch (43-cm) deep solum containing abundant rock fragments. That on the northeast exposure was a fine Calcic Cryoboroll with a 20-inch (51-cm) deep solum relatively free of rock. Both had ustic moisture and cryic temperature soil climatic regimens.

Vegetation of the general area (fig. 1) was a mosaic of mountain grasslands and coniferous forests comprised primarily of limber pine (*Pinus flexilis*), lodgepole pine (*Pinus contorta*), and Douglas-fir (*Pseudotsuga menziesii*). Vegetation on the grassland study sites consisted of variations in the Idaho fescue (*Festuca idahoensis*)/bluebunch wheatgrass (*Agropyron spicatum*) habitat type (Mueggler and Stewart 1980). The southwest sloping site was typical of this type, whereas the northeast sloping site represented the western needlegrass (*Stipa occidentalis*) phase of the habitat type with more moisture available for plant growth. The Idaho fescue/bluebunch wheatgrass habitat type is considered to be one of the most abundant mountain grassland types in southwestern Montana (Mueggler and Stewart 1980).

METHODS

Herbage production was determined from 1964 through 1973 by sampling 50 permanent 4.8 ft^2 (0.45 m^2) plots on each study site. These plots were distributed in a series of 10 sets, 5 plots per set, over a relatively

Figure 1.—Mountainous rangelands in southwestern Montana, typical of the vegetation and terrain of the study sites, often consist of a mosaic of tussock grasslands and coniferous forests.

uniform portion of the site. Peak standing crop of the current year's biomass was measured when the vegetation appeared to have achieved full growth and just before many species began to dry. This generally occurred between the middle and end of July.

Production was determined by combining percent-weight estimates and clipping, because estimating species weights as a percentage of total yield is believed to be more efficient than estimating directly as weight units (Hutchings and Schmautz 1969). Each year one plot in each set of five was protected from livestock grazing by a wire cage. This plot was considered the reference plot for that set for that particular year. The reference plot was changed each year so that no one plot served as a reference more than once in 5 years. Total herbage production on each of the remaining four plots in a set was estimated as a percentage of the total production on the set's reference plot. These estimates were adjusted to compensate for current livestock utilization, which usually was slight. The weight of each species on a plot was then estimated as a percentage of the total production on the plot; these estimates were also adjusted to compensate for utilization. Total vegetation on the reference plot was then clipped to ground level and weighed, with individual weights of the four major species on the plot recorded separately. Comparing the estimated percent-weight on the reference plot with the computed percent-weight for each of the clipped species served as a continual check on the accuracy of the estimates and permitted the estimator to adjust for drift in his estimates. The total production on the clipped reference plot was used to translate the percentage figure for total production on the estimated plots to actual weight. The green weight of individual species on each plot could then be computed from their respective percentages. The clipped material was subsequently dried, the percentage dry matter obtained for all important species, and all green weights converted to production of air-dry material.

I originally thought that clipping one-fifth of the plots to ground level every year would not affect overall production estimates appreciably in subsequent years. It became apparent, however, that the initial decline in vegetation vigor on the clipped plots persisted longer than anticipated. I therefore established a new series of 50 plots parallel to the existing plots on each site. Both old and new plots were inventoried in the same year to provide for the minor adjustment factors needed to

equate the new plots with the old. Production for 1970 through 1973 is from the adjusted second series of plots.

Developmental growth stage was recorded for common species at each site at weekly intervals. Individual plants of selected species were marked for repeated observation; 40- by 80-ft (12- by 24-m) enclosures protected these plants from livestock. Dates of various development stages for each species were determined from the marked plants plus supplemental observations of the development of surrounding plants. If development of a marked individual appeared abnormal, a more typical specimen was selected for subsequent observation. The sites were visited each week from the onset of active growth in the spring (usually early May) until most species were dormant (late October).

The developmental stages discussed in this report are:

Forbs

Growth starts—first evidence of current year's growth.
First bloom—first fully developed blossoms.
Bloom over—approximately 90 percent of flowering completed.
Dissemination starts—first evidence of seed drop.
Plant dried—at least 90 percent of the herbage dried.

Grasses

Growth starts—first evidence of current year's growth.
Flower stalks appear—first evidence of booted flowering culms.
Flowers in bloom—approximately 25 percent of flowers in anthesis.
Seed ripe—approximately 25 percent of seed mature as judged by hardness of the caryopsis.
Plant dried—at least 90 percent of the herbage dried.

Weather was monitored on each site from May 1 to October 31 each year. Usually the snowpack had melted on the southwest exposure by late April and on the northeast exposure about 1-1/2 weeks later in early May. Although occasional snowstorms were not unusual in May, June, September, and October, the winter snowpack generally did not begin to accumulate until sometime in November. Instruments were placed on each site to measure air and soil temperature, relative humidity, precipitation, soil moisture, wind, and solar radiation. These instruments were within a 40- by 80-ft (12- by 24-m) enclosure at least 10 ft (3 m) from the barbed-wire fence.

Air temperature and relative humidity were recorded continuously by a hygrothermograph installed 4.5 ft (1.4 m) above ground in a standard shelter. Soil surface temperatures were continuously recorded in the sun and in the shade by a soil thermograph; a continuous record of temperature was also obtained at a 2-inch (5-cm) depth. Duplicate readings of soil temperature and soil moisture at 8, 20, and 40 inches (20, 50, and 100 cm) were taken at weekly intervals by use of Colman fiberglass soil moisture units buried in undisturbed soil beneath existing vegetation. Recording precipitation gages shielded by wind deflectors measured periodicity, intensity, duration, and total fall. The amount of wind each site received was measured by totalizing 3-cup anemometers mounted 6 ft (1.8 m) above ground and read weekly. Solar radiation was continuously recorded by bimetalic actinographs.

A total of 90 weather variables were compiled for possible correlation with plant growth. Of these, 20 were subjectively chosen as most likely to have a bearing upon herbage production and 7 selected as likely to affect plant development. The relationships between weather and plant growth discussed in this report are based upon correlation and regression analyses with these selected weather variables. Only the vegetation classes and more productive species were evaluated.

RESULTS AND DISCUSSION

Production Variability

Production of vegetation on the northeast exposure was almost double that on the southwest exposure. In 9 of the 10 years it ranged from 172 to 235 percent of that on the southwest exposure. This production difference was comprised principally of forbs. Very likely this difference can be attributed to a greater availability of soil moisture for growth on the northeast exposure, stemming from less evaporative loss, greater storage capacity in the soil mantle, and differences in snow accumulation because of blowing and drifting patterns.

Total vegetation production varied appreciably between years (table 1). Production during the best year on the southwest exposure was approximately 1-1/3 that during the poorest year, whereas the best year on the northeast exposure was over twice that of the poorest year. The coefficient of variation for total production over the 10-year period was 12 percent on the southwest exposure and 19 percent on the northeast exposure. During the first year of the study, however, total production on the northeast exposure was inexplicably low (724 lb/acre [811 kg/ha] compared to 1,217 lb/acre [1 364 kg/ha] for the next lowest year) and unalined with production on the southwest exposure. Discarding this one value resulted in a mean production of 1,377 lb/acre (1 544 kg/ha) with a coefficient of variation of 10 percent on the northeast site. In this case the relative variability in total production between years would be approximately the same on both sites irrespective of the productivity levels of the sites. This agrees with the conclusions of Mueggler and Stewart (1981) that there is no pronounced difference between good and poor sites in the **proportionate** amount of variability between years in total standing crop.

The amount of yearly variability in production by vegetation classes considerably exceeded that of total production. The southwest exposure produced well over two-times as much graminoids and 1-1/2 times as much forbs in the highest year than in the lowest year; the northeast exposure varied more yet in that it produced 2-3/4 times as much graminoids and 2-1/2 times as much forbs in the high than in the low year (table 1). The coefficient of variation between years for graminoids on both sites approached 25 percent; it was 14 percent for forbs on the southwest sloping site and 21 percent on the northeast sloping site. Interestingly, annual production of graminoids was not related to the annual production of forbs. The nonsignificant correlation coefficients

Table 1a.—*Range, mean, and standard deviation (s) of herbage production over a 10-year period*

Species	Southwest exposure			Northeast exposure		
	Range	Mean	s	Range	Mean	s
	kg/ha, air dry					
Total vegetation	663-917	767	94	811-1793	1471	272
Total graminoids	270-586	407	101	228- 628	446	114
Total forbs	276-422	359	51	583-1451	1024	216
GRAMINOIDS						
Agropyron spicatum	25-142	65	38	16- 111	43	28
Agropyron caninum	-	-	-	< 1- 11	4	3
Bromus anomalous	-	-	-	6- 17	10	4
Carex filifolia	30- 57	42	9	1- 14	7	5
Carex stenophylla	12- 45	22	11	-	-	-
Danthonia intermedia	-	-	-	24- 233	115	78
Festuca idahoensis	163-374	248	71	82- 246	170	41
Koeleria cristata	9- 18	15	3	< 1- 15	4	4
Poa spp.	< 1- 15	4	5	< 1- 15	4	5
Stipa occidentalis	7- 29	13	8	25- 100	63	25
FORBS						
Achillea millefolium	10- 50	26	13	13- 67	40	16
Agoseris glauca	19- 43	29	7	1- 66	20	20
Anemone patens	2- 7	4	2	7- 61	36	16
Antennaria rosea	10- 35	21	7	3- 21	10	4
Arenaria congesta	< 1- 20	10	6	25- 78	42	16
Astragalus miser	< 1- 9	3	3	< 1- 12	5	4
Besseya wyomingensis	< 1- 3	< 1	< 1	-	-	-
Campanula rotundifolia	9- 16	14	4	5- 35	19	10
Cerastium arvense	17- 42	26	8	26- 155	72	36
Clematis hirsutissima	-	-	-	5- 32	19	9
Erigeron subtrinervis	-	-	-	42- 130	87	24
Eriogonum umbellatum	-	-	-	34- 100	59	19
Frasera speciosa	14- 39	23	9	-	-	-
Gaillardia aristata	14- 34	23	6	13- 76	26	18
Galium boreale	30- 72	49	13	19- 55	28	10
Gentiana affinis	2- 13	5	3	-	-	-
Geranium viscosissimum	-	-	-	71- 186	114	40
Geum triflorum	2- 14	7	4	51- 156	109	29
Gilia congesta	< 1- 7	2	2	-	-	-
Linum perenne	2- 30	13	11	< 1- 9	3	4
Lupinus serecius	-	-	-	110- 263	167	55
Myositis sylvatica	-	-	-	< 1- 23	9	8
Oxytropis serecia	1- 6	4	1	-	-	-
Pedicularis contorta	38- 67	48	10	-	-	-
Phlox hoodii	1- 5	3	1	-	-	-
Phlox multiflora	-	-	-	27- 118	67	35
Polygonum bistortoides	-	-	-	< 1- 7	3	2
Potentilla gracilis	-	-	-	< 1- 22	5	6
Taraxicum officinale	< 1- 4	2	2	-	-	-
Townsendia mensana	< 1- 3	1	1	-	-	-
Viola adunca	-	-	-	46- 126	94	25
Zygadenus venenosus	< 1- 6	2	2	< 1- 11	3	3

Table 1b.—*Range, mean, and standard deviation (s) of herbage production over a 10-year period*

Species	Southwest exposure			Northeast exposure		
	Range	Mean	s	Range	Mean	s
	lb/acre, air dry					
Total vegetation	592-818	684	84	724-1599	1312	243
Total graminoids	241-523	363	90	203- 560	398	102
Total forbs	246-376	320	46	520-1295	914	193
GRAMINOIDS						
Agropyron spicatum	22-127	58	34	14- 99	38	25
Agropyron caninum	-	-	-	< 1- 10	3	3
Bromus anomalous				5- 15	9	3
Carex filifolia	27- 51	38	8	1- 12	7	4
Carex stenophylla	10- 40	20	10	-	-	-
Danthonia intermedia	-	-	-	21- 208	103	69
Festuca idahoensis	146-333	222	64	73- 220	152	37
Koeleria cristata	8- 16	13	3	< 1- 13	4	4
Poa spp.	< 1- 14	4	5	< 1- 13	4	4
Stipa occidentalis	6- 26	12	7	22- 89	56	22
FORBS						
Achillea millefolium	9- 45	23	12	12- 60	34	14
Agoseris glauca	17- 38	26	6	1- 59	18	18
Anemone patens	2- 7	4	2	6- 55	32	15
Antennaria rosea	9- 31	18	7	3- 19	9	4
Arenaria congesta	< 1- 18	9	6	22- 70	38	14
Astragalus miser	< 1- 8	3	2	< 1- 11	4	4
Besseya wyomingensis	< 1- 2	< 1	1	-	-	-
Campanula rotundifolia	8- 14	12	3	4- 31	17	9
Cerastium arvense	15- 38	23	8	23- 138	64	32
Clematis hirsutissima				4- 28	17	8
Erigeron subtrinervis				39- 116	78	23
Eriogonum umbellatum				30- 89	44	17
Frasera speciosa	13- 34	21	8	-	-	-
Gaillardia aristata	12- 30	21	6	12- 68	23	16
Galium boreale	26- 64	44	11	17- 49	25	9
Gentiana affinis	2- 11	5	3	-	-	-
Geranium viscosissimum				64- 166	102	35
Geum triflorum	2- 13	7	3	45- 139	98	26
Gilia congesta	< 1- 6	2	2	-	-	-
Linum perenne	2- 27	12	10	< 1- 8	3	3
Lupinus serecius				98- 235	149	49
Myositis sylvatica	-	-	-	< 1- 21	8	7
Oxytropis serecia	1- 6	3	2	-	-	-
Pedicularis contorta	34- 59	43	9	-	-	-
Phlox hoodii	1- 5	3	1	-	-	-
Phlox multiflora	-	-	-	24- 105	60	31
Polygonum bistortoides	-	-	-	< 1- 6	2	2
Potentilla gracilis				< 1- 20	5	6
Taraxicum officinale	< 1- 4	2	2	-	-	-
Townsendia mensana	< 1- 3	1	1	-	-	-
Viola adunca	-	-	-	41- 112	84	23
Zygadenus venenosus	< 1- 5	2	2	< 1- 10	2	3

(r) between these two vegetation classes were −0.42 on the southwest site and 0.29 on the northeast site. Apparently, the interactions of the many factors constituting "weather" on these mountain grasslands differentially affected the grasses and forbs. These findings contrast somewhat with those of Blaisdell (1958) who, over a 13-year period on sagebrush-grass range, obtained a coefficient of variation of 29 percent for graminoids and 23 percent for forbs, and a significant positive correlation in production between the two (r = 0.64*).[1]

Although forb production on the southwest exposure over the 10-year period was significantly correlated with forbs on the northeast exposure (r=0.64*), the production of graminoids was not correlated between exposures.

The relative variation in production between years was frequently greater yet for individual species (table 1). The very great difference between years in relative amounts of some minor species that contribute little to overall production was probably caused by sampling inadequacies. Some major species such as *Agropyron spicatum, Danthonia intermedia*, and *Stipa occidentalis*, however, produced between four and nine times more during the best than during the poorest year. These species had coefficients of variation ranging from 40 to 67 percent. The production of other major species did not fluctuate so greatly. *Festuca idahoensis, Erigeron subtrinervis, Lupinus serecius,* and *Geranium viscosissimum* varied less than 300 percent among years, and had coefficients of variation between 24 and 35 percent. Correlation in yearly production between major graminoid species was poor, with two exceptions: *Agropyron spicatum* was significantly positively correlated with *Festuca idahoensis* (r = 0.76**) on the southwest exposure, and negatively correlated with *Danthonia intermedia* (r = −0.64*) on the northeast exposure. Yearly production of only three major forbs was significantly correlated; these were *Geranium viscosissimum* and *Erigeron subtrinervis* (r = 0.87**), *Geranium viscosissimun* and *Lupinus serecius* (r = 0.71*), and therefore *Erigeron subtrinervis* and *Lupinus serecius* (r = 0.66*). These findings support Blaisdell's (1958) conclusions that (a) individual species vary greatly in their response to the same environmental factors, and (b) increased yield of one can compensate for decreased yield of another and thus dampen oscillations in total production.

Relationship of Production to Weather

The 20 weather variables selected as most likely affecting plant yield are shown in tables 2 and 3, as are their respective correlation coefficients with major plant species and vegetation classes on both sites. Surprisingly few of these individual weather variables were significantly correlated with the production of major species or of vegetation classes. More disturbing, some of the highest correlations appear at first glance to be contrary to ecological expectation. More significant correlations appeared on the less productive southwest sloping site than on the northeast site.

Agropyron spicatum production on both sites and *Festuca idahoensis* and *Galium boreale* production on the southwest exposure were slightly favored by cool June air temperatures, while the production of *Danthonia intermedia* and *Achillea millefolium* was favored by warm June temperatures. Cool July soil temperatures appeared to favor somewhat the production of *Carex filifolia, Carex stenophylla*, and *Achillea millefolium.* Windy May weather stimulated *Festuca idahoensis* and *Galium boreale* on the southwest exposure and *Agropyron spicatum* on the northeast exposure, but inhibited *Carex filifolia* and *Achillea millefolium.* May, June, and July precipitation appeared to favor production of *Geum triflorum*, perhaps by extending its growing period, whereas May precipitation favored *Stipa occidentalis*, and precipitation the prior fall favored *Danthonia intermedia.* Strong negative correlations were found between the production of *Agropyron spicatum* and precipitation the prior fall on both the southwest (r = −0.91**) and northeast (r = −0.89**) exposures; similiar negative correlations were found for *Festuca idahoensis* (r = −0.86**) and *Peducularis contorta* (r = −0.74**) on the southwest exposure. These negative correlations generally carried through to the amount of soil moisture at the beginning of plant growth in the spring, which is sensible since fall precipitation and soil moisture in the spring are closely related.

This strong negative effect of fall precipitation on the following year's production of major mountain grassland species is surprising in light of the positive correlations previously reported for various range types. For example, Johnston and others (1969) found positive correlations (r = 0.75** to 0.82**) between fall soil moisture and the following year's yield of *Festuca scabrella* rangelands in southern Canada, and Sneva (1977) found that yields of *Agropyron desertorum* in southeastern Oregon were positively correlated (r = 0.75**) with July through May precipitation.

A likely explanation for my negative correlations lies in a probable negative relationship on these mountain grasslands between fall regrowth and production the following year. Active summer growth of *Agropyron spicatum* and *Festuca idahoensis* on these sites generally ceases and plants begin to cure in early to mid-August because of inadequate soil moisture to support growth (Mueggler 1971, 1972a). Appreciable late summer and early fall precipitation frequently results in fall regrowth, particularly of bunchgrass, but other plants as well if air and soil temperatures are amenable for growth. McIlvanie (1942) found the depletion of carbohydrate reserves by the initial phases of fall regrowth in *Agropyron spicatum* to parallel that ordinarily occurring during initial spring growth. Trlica and Cook (1972) observed that fall regrowth caused reductions in total available carbohydrate reserves in *Agropyron cristatum* and *Elymus junceus*, and that increasing the amount of fall regrowth by watering caused significant reductions of available carbohydrate levels which were not replenished before fall quiescence. The positive effect of levels of stored reserves on subsequent production was

[1] * indicates significance at the 95-percent probability level, and ** at the 99-percent level.

site (probability * = >95, ** = >99)

Weather factors	Total vegetation	Total graminoids	Total forbs	*Agropyron spicatum*	*Festuca idahoensis*	*Carex filifolia*	*Carex stenophylla*	*Achillea millefolium*	*Agoseris glauca*	*Galium boreale*	*Pedicularis contorta*
Precipitation											
Prior Sept. thru Oct.	0.83*	.96**		.91**	.86**	.89		0.58	0.29	0.48	.24*
May	20	18	14	17	31	12	11	18	01	51	48
June	50	50	39	39	45	41	21	28	03	26	28
July	08	13	05	01	08	14	11	16	06	16	01
May + June	63	74	56	45	53	62	37	59	03	06	55
May + June + July	56	68	19	4	17	37	05	08	01	12	45
Prior Sept. Oct. + May	07	24	47	11	44	07*	01	07	21	48	04
Soil moisture at 100 cm											
At beginning of growth	41	44*	44*	21*	32*	05	....	....	06	01	16
May 1	34	31	21	44	31	36	28	01	11	39	24
June 1	16	21	30	01	15	10	01	40	16	54	13
July 1	07	12	24	07	24	....	16	12	21	44	11
Average maximum air temperature											
May	42	34	37	31	32	36	39	32	36	01	49
June	34	37*	30	....	....	28	35	30*	29	25*	30
July	02	04	04	06	07	01	42*	04	44*	08	29
Average maximum soil temperature at 5 cm											
May	28	32	21	26	31	31	27	24	24	15	39
June	04	07	01	07	03	03	04	02	14	01	14
July	11	11	06	03	06	....	....	00	08	36	15
Average wind velocity											
May	04	06	03	06	07*	10**	06	08*	04	44*	02
June	06	08	06	04	02	01	03	02	43	28	01
July	01	01	01	02	03	04	06	02	43	01	11

Table 3 [illegible]

Weather factors	Total vegetation	Total graminoids	Total forbs	*Agropyron spicatum*	*Festuca idahoensis*	*Danthonia intermedia*	*Stipa occidentalis*	*Erigeron subtrinervis*	*Geranium viscosissimum*	*Geum triflorum*	*Lupinis sericeus*
Precipitation											
Prior Sept. thru Oct.	06	12	09	17*	06	21*	19	02	24	32*	11
May	08	07	11	06	11	02	12	03	01	01	14
June	08	01	04	06	08	01	08	06	01	01	07
July	01	03	03	01	04	01	03	06	04	03	09
May + June	04	04	04	04	04	01	04	04	01	02*	16
May + June + July	04	02	03	03	03	01	04	03	01	01*	10
Prior Sept. Oct. + May	01	01	03*	01	01	01	01	01	11	....	01
Soil moisture at 100 cm											
At beginning of growth	08	11	06	11	06	11	11	07	10	11	06
May 1	10	07	11	11	11	07	08	08	07	07	11
June 1	03	03	03	09*	03	09*	08	03	03	03	04
July 1	01	01	01	01	01	04	03	01	01	01	01
Average maximum air temperature											
May	03	04	03	03	01	03	04	03	04	04	03
June	03	04	03	04	03	06**	03	03	04	03	03
July	06	07	04	03	03	03	03	03	03	02	03
Average maximum soil temperature at 5 cm											
May	03	04	01	03	02	03	03	04	03	03	04
June	01	01	01	03	01	03	01	01	01	01	01
July	01	01	01	01	01	01	01	01	01	01	01
Average wind velocity											
May	03	03	03	04*	03	03	03	03	03	03	03
June	03	03	03	03	03	03	03	03	03	03	03
July	04*	04	04	03	03	03	03	03	04	04	04

[illegible]

demonstrated by McKendrick and Sharp (1970) who found that the weight of etiolated tillers per *Agropyron cristatum* plant (a direct index to reserves available for growth) was highly correlated ($r = 0.97^{**}$) with subsequent herbage yield. White (1973) concluded that low carbohydrate reserves reduce the initial growth rate which in turn can affect subsequent exponential growth. Besides the direct effect of slowing initial and subsequent growth rates, low carbohydrate stores are likely to place plants at a competitive disadvantage. I found that reducing the vigor of *Agropyron spicatum* and *Festuca idahoensis* by heavy clipping, but not that of competing vegetation, resulted in a 41- to 43-percent decrease in herbage production the following growing season (Mueggler 1970, 1972b).

Thus it appears that reducing carbohydrate reserves of certain mountain grassland plants, whether by grazing, clipping, or fall regrowth, lowers the capacity of these plants to produce well the following year. This may be caused by a lack of start-up carbohydrates as well as reduced ability to compete with associates that have remained vigorous. In either case, fall regrowth probably accounts for lower production the following year and consequently in the negative correlation with fall precipitation.

On range sites where fall regrowth apparently does not adversely affect growth the following year, the climate may permit replacement of carbohydrate reserves after initial regrowth depletion and before winter quiescence. On my mountainous sites, however, air and soil temperatures may have been inadequate for the extended period of growth required for replacement of the carbohydrates depleted by the initiation of fall regrowth. This possibility is supported by the failure of *Festuca idahoensis* production on the northeast exposure to be negatively correlated with fall precipitation. The orientation of the northeast exposure resulted in lower fall temperatures than on the southwest exposure (Mueggler 1971); these lower temperatures may have been inadequate to support fall regrowth of *Festuca idahoensis*. On the other hand, the average date that *Festuca idahoensis* dried on the northeast exposure was October 7, which was 16 days later than on the southwest exposure. Late September and early October precipitation may simply have prolonged *Festuca idahoensis* growth on the northeast exposure while it initiated regrowth on the southwest site. Unfortunately, I did not obtain data on fall regrowth over the 10-year study period to verify a relationship between fall precipitation and fall regrowth.

Stepwise multiple regression analyses were used to help identify the combination of weather variables that would best account for the yearly variation in production of vegetation classes and of several important individual species. Three weather variables were sufficient to account for at least 88 percent of the yearly variation in production of all classes and species evaluated on the southwest exposure (table 4). Ninety-seven percent of the variation in the production of total graminoids on the southwest exposure was accounted for by a model incorporating prior September-October precipitation, July precipitation, and July wind. The three-parameter models were less effective in accounting for production variability on the more productive northeast exposure (table 5). Although 97 percent of the variation in *Agropyron spicatum* was accounted for by a model comprised of prior September-October precipitation, July 1 soil moisture, and June soil temperature, models for the other species and vegetation classes accounted for only 54 to 82 percent of the variation.

Different combinations of weather parameters best accounted for production variations of different classes and species. This supports the previous conclusion that species differ in their response to the same environmental factors. Contrary to expectations, however, the best-fit models for like vegetation classes and like species differed appreciably between the southwest and northeast exposure. Only in the case of *Agropyron spicatum* did models selected for one site perform well on the opposing site. The best model for this species on the southwest exposure had a coefficient of multiple determination (R^2) of 0.92^{**} on the southwest exposure and 0.94^{**} on the northeast exposure; the best model on the northeast exposure had an R^2 of 0.97^{**} on the northeast exposure and 0.90^{**} on the southwest exposure. In no other instance did the model best fitting one site exceed an R^2 of 0.55 on the opposing site. Yet, both sites were occupied by the same general type of vegetation, were at the same elevation and within 600 ft (183 m) of one another, but on opposite exposures. This suggests that great care should be exercised in extending to broad areas models developed at a single location, especially on environmentally variable mountainous rangelands.

Table 4a.—*Multiple linear regression of best three weather variables selected for predicting dry herbage production by vegetation classes and four major species on a shallow soil, southerly exposure at 2 164 m elevation*

	Total vegetation	Total graminoids	Total forbs	*Agropyron spicatum*	*Festica idahoensis*	*Galium boreale*	*Pedicularis contorta*
Regression constant (kg/ha)	1 577	954	1 214	455	2 310	294	208
				Coefficients			
Weather variables:							
Precipitation (inches):							
Prior Sept.-Oct.	-122	-109		-36			-15
July		- 29				4.2	
Soil moisture at 100 cm depth (log ohms resistance):							
At beginning of growth	-140		-127				-18
On June 1	71		[illegible]				
On July 1					-838		
Temperature (°F):							
Air, average max. May			-8 5		-8.0		
Air, average max. June						-5.7	
Soil, 5 cm, average max. June				[illegible]			
Wind (average mi/h)							
May					[illegible]		
June						18	
July		47		[illegible]			-5.8
Coefficient of multiple determination (R^2)	[illegible]	0.97**	0.93**	0 92**	0.94**	0.96**	0.88**
Standard error of estimate (kg/ha)	39.0	22 9	16.9	13.2	20.7	[illegible]	4 2
Average production (kg/ha)	766	407	359	65	248	49	48

[1]Probability, * = 95 , ** = >99 ;

Table 4b.—*Multiple linear regression of best three weather variables selected for predicting dry herbage production by vegetation classes and four major species on a shallow soil, southerly exposure at 7,100 ft elevation*

	Total vegetation	Total graminoids	Total forbs	*Agropyron spicatum*	*Festuca idahoensis*	*Galium boreale*	*Pedicularis contorta*
Regression constant (lb/acre)	1,407	851	1,083	406	2,061	262	186
				Coefficients			
Weather variables:							
Precipitation (inches):							
Prior Sept.-Oct.	109	-97		32			13
July		26				3 7	
Soil moisture at 100 cm depth (log ohms resistance):							
At beginning of growth	125		-113				16
On June 1	63		69				
On July 1					748		
Temperature (°F):							
Air, average max. May			-7.6		-7.1		
Air, average max. June						5.1	
Soil, 5 cm, average max. June				-6.3			
Wind (average mi/h)							
May					174		
June						16	
July		-42		13			-5.2
Coefficient of multiple determination (R^2)	0 88**[1]	0.97**	0.93**	0.92**	0.94**	0.96**	0.88**
Standard error of estimate (lbs/acre)	34.8	20.4	15.1	11.8	18.5	2.7	3.7
Average production (lb/acre)	684	363	320	58	221	44	43

[1]Probability * = 95 , ** = 99

Table 5a.—*Multiple linear regression of best three weather variables selected for predicting dry herbage production by vegetation classes and four major species on a deep soil, northerly exposure at 2 164 m elevation*

Regression constant (kg/ha)	Total vegetation -10 004	Total graminoids -790	Total forbs -7 825	*Agropyron spicatum* 282	*Festuca idahoensis* 587	*Geranium viscosissimum* 150	*Lupinus serecius* 404
				Coefficients			
Weather variables:							
Precipitation (inches):							
Prior Sept.-Oct.				-24			
May							26
June					17		
May-June	174						
Prior Sept.-Oct. and May-July		-6.6	292				
Soil moisture at 100 cm depth (log ohms resistance):							
At beginning of growth	345					29	83
On May 1					-24		
On June 1			-412		-121		-176
On July 1			2,202	39			
Temperature (°F):							
Air, average max. June	154	31					
Soil, 5 cm, average max. June				-5.0			
Soil, 5 cm, average max. July						4.9	
Wind (average mi/h):							
July		-121				-85	
Coefficient of multiple determination (R^2)	0.72*[1]	0.65	0.65	0.97**	0.54	0.77*	0.82*
Standard error of estimate (kg/ha)	176	83	157	6	34	23	28
Average production (kg/ha)	1 471	446	1 025	43	170	114	167

[1]Probability: * = >95%; ** = >99%.

Table 5b.—*Multiple linear regression of best three weather variables selected for predicting dry herbage production by vegetation classes and four major species on a deep soil, northerly exposure at 7,100 ft elevation*

Regression constant (lb/acre)	Total vegetation -8,924	Total graminoids -705	Total forbs -6,980	*Agropyron spicatum* 195	*Festuca idahoensis* 533	*Geranium viscosissimum* 134	*Lupinus serecius* 361
				Coefficients			
Weather variables:							
Precipitation (inches):							
Prior Sept.-Oct.				-20			
May							23
June					15		
May-June	155						
Prior Sept.-Oct. and May-July		-5.9	261				
Soil moisture at 100 cm depth (log ohms resistance):							
At beginning of growth	308					26	74
On May 1					-21		
On June 1			-368		-108		-157
On July 1			1,965	35			
Temperature (°F):							
Air, average max. June	137	28					
Soil, 5 cm, average max. June				-4.5			
Soil, 5 cm, average max. July						4.4	
Wind (average mi/h):							
July		-108				-76	
Coefficient of multiple determination (R^2)	0.72*[1]	0.65	0.65	0.97**	0.54	0.77*	0.82*
Standard error of estimate (lb/acre)	157	74	140	6	31	21	25
Average production (lb/acre)	1,312	398	914	38	152	102	149

[1]Probability: * = >95%; ** = >99%.

Variation in Seasonal Development

Apparent growth activity in the spring on these mountain grasslands frequently began at different times for the various species and usually spanned an almost 3-week period (tables 6, 7, and 8). *Lomatium cous, Zigadenus venenosus, Fritillaria pudica,* and *Anemone patens* were among the earliest to begin growth and *Lupinus serecius, Gaillardia aristata,* and *Antennaria rosea* were among the last. Growth usually began almost 1 week later on the northeast than on the southwest exposure. This lag also varied with species, averaging as many as 11 days later for *Oxytropis serecia* and as few as 3 days for *Cerastium arvense*. The lag in growth on the northeast exposure was probably caused by an average 9-day later melt of the winter snowpack on the northeast than on the southwest exposure. Growth of the earliest species usually began within 1 week following snowmelt. During the first 5 years of this study I found that an 1,100 ft (335-m) elevational increase delayed the beginning of growth for individual species from 19 to 37 days, or an average of 28 days for all species (Mueggler 1972a).

The greatest difference between years in which growth began was 43 days for *Linum perenne*; the least difference was 20 days for *Agoseris glauca* and *Achillea millifolium* on the southwest exposure. With most species, however, the difference between the earliest and latest starting dates for growth over the 10-year period was from 25 to 30 days. Most of the species should begin growth in 2 out of 3 years within 8 to 12 days of their mean date for beginning growth. Costello and Price (1939) recorded up to 50 days variation in the beginning of growth for some species over a 10-year period on mountain herblands in Utah. I found no significant difference between exposures in the amount of this year-to-year variation.

The onset of flowering of the various forbs generally spread over almost a 10-week period. The early spring flowers such as *Lomatium cous, Anemone patens,* and *Fritillaria pudica* usually bloomed within 1 to 2 weeks following the start of growth. The floral display then progressed through the growing season until the late-flowering species such as *Erigeron subtrinervis, Gaillardia aristata, Campanula rotundifolia,* and *Galium boreale* began blooming over 2 months later. The flowering sequence of the various species is the order of species names listed in tables 6, 7, and 8. The different grasses usually bloomed within a 2-week period, 8 to 10 weeks after growth began and 2 to 4 weeks after their flower stalks appeared. The various species of forbs and grasses bloomed from 1 to 10 days later on the northeast exposure than on the southwest exposure; this delay averaged 6 days for all species, about the same as the delay in start of growth. Generally the delay was longer and coincided more with the delay in start of growth for the early-blooming species than for those that bloomed later. Apparently, the effects of exposure on flowering tend to become ameliorated as the season advances. Costello and Price (1939) observed that development on north exposures lagged about 10 days behind that on south exposures on mountain herblands in Utah, whereas Bliss (1956) found only a 2- to 4-day lag on north exposures in the alpine tundra of southern Wyoming. An 1,100-ft (335-m) elevational rise caused blooming of individual species on these mountain grasslands to be delayed from 11 to 29 days, or an average delay of 20 days for all species (Mueggler 1972a).

Maximum year-to-year differences in initiation of flowering ranged from 5 to 52 days, and averaged 23 days for all species. There could therefore be as many as 23 days difference between early and late years in the floral display. The flowering date of late-blooming species varied considerably less between years than did that of early-blooming plants. In 2 out of 3 years, the late-blooming species can be expected to flower within 4 to 6 days of their respective average flowering date, whereas the early-blooming species can be expected to flower within about 10 days of their average date. The amount of yearly variability did not differ significantly between exposures.

The duration of flowering (from first bloom to when blooming ceased) was conspicuously species-dependent. Some forbs such as *Agoseris glauca, Zigadenus venenosus,* and *Antennaria rosea* completed their flowering phase on the average within 2 weeks. Others, such as *Lomatium cous, Frasera speciosa,* and *Achillea millefolium* took as long as 4 weeks to finish blooming. The length of the flowering period did not appear related to whether a species tended to bloom early or late in the growing season, nor was it significantly related to exposure.

The start of seed dissemination in the forbs stretched over an 8-week period, usually beginning in early July with *Agoseris glauca* and *Anemone patens*, and ending in late August with *Achillea millefolium, Erigeron subtrinervis,* and *Gaillardia aristata*. The composites were usually among the last to begin dissemination, averaging about 2 weeks later than the average of the other forbs. From 1 to 2 months usually elapsed between initiation of flowering and initiation of seed dissemination. Some species, such as *Agoseris glauca, Cerastium arvense,* and *Polygonum bistortoides* began seed dissemination within about 4 weeks following the onset of flowering, whereas others such as *Fritillaria pudica* and *Lomatium cous* required almost 9 weeks. The grasses usually required about 3 to 4 weeks to form ripe seed from the time they began to flower. Although a considerable lag in seed dissemination occurred on the northeast exposure for some species, such as an average 11 days for *Dodecatheon conjugans*, the mean dissemination date for all species did not differ significantly between exposures because of the high variability among species.

Maximum variation between years in the start of dissemination ranged from less than 3 weeks for *Zigadenus venenosus, Geum triflorum,* and *Polygonum bistortoides* to over 6 weeks for *Pedicularis contorta* and *Agoseris glauca* on the southwest exposure. The average variation between years for all forbs amounted to 26 days. This was similar to the average yearly variation in flowering. Overall, dissemination can be expected to start in 2 out of 3 years within 8 days of the average

Table 6.—*Range, mean, and standard deviation (s) of phenological event dates for prominent forbs on a mountain grassland with a southwest exposure at 7,100 ft (2 164 m) elevation over a 10-year period*

Species	Growth starts			First bloom			Blooming over			Dissemination starts			Plant dried		
	Range	Mean	s	Range	Mean	s	Range	Mean	s	Range	Mean	s	Range	Mean	s
			Days			Days			Days			Days			Days
Lomatium cous	4/17-5/12	4/29	10.7	4/20-5/24	5/9	12.0	5/22-6/27	6/12	11.0	6/25-7/23	7/11	8.1	7/10-8/17	7/18	11.8
Anemone patens	4/18-5/16	5/2	9.7	4/26-5/25	5/9	10.3	5/8-6/10	5/25	11.2	6/21-7/16	7/4	8.3	8/15-9/4	8/25	5.8
Fritillaria pudica	4/20-5/16	5/2	9.5	5/2-5/30	5/14	9.4	5/18-6/10	5/31	7.9	7/12-8/5	7/22	6.7	6/25-8/5	7/22	12.0
Dodecatheon conjugens	4/25-5/16	5/5	8.0	5/5-6/3	5/18	10.9	5/15-6/16	6/3	11.6	6/21-7/16	7/5	8.0	6/11-8/1	7/4	14.1
Saxifraga montanensis	4/18-5/14	5/1	9.5	5/8-6/7	5/24	10.1	5/25-6/26	6/12	10.7	6/27-7/16	7/6	6.4	7/10-7/26	7/17	5.2
Agoseris glauca	4/26-5/16	5/5	8.3	5/16-7/7	6/2	14.7	5/25-7/17	6/12	14.2	6/15-9/4	7/1	23.9	7/1-8/16	7/17	13.8
Frasera speciosa	4/23-5/20	5/5	10.0	5/10-6/18	6/4	11.5	6/19-7/11	7/3	7.1	7/6-8/1	7/22	7.8	7/15-9/2	8/13	15.9
Geum triflorum	4/23-5/18	5/4	8.6	5/17-6/12	6/4	9.2	5/30-6/30	6/19	10.3	7/9-7/26	7/17	6.3	8/15-9/19	8/29	12.2
Delphinium bicolor	4/21-5/20	5/6	10.9	5/22-6/26	6/9	12.2	6/8-7/18	7/1	12.1	6/25-7/23	7/11	9.5	6/20-8/14	7/15	15.1
Polygonum bistortoides	4/23-5/16	5/4	8.0	6/1-6/23	6/12	7.0	6/29-7/20	7/7	6.2	7/2-7/20	7/12	5.7	7/17-8/2	7/25	5.1
Cerastium arvense	4/25-5/20	5/7	8.7	5/28-6/27	6/13	9.8	6/18-7/12	7/1	7.7	7/2-7/26	7/12	7.9	7/30-9/5	8/12	11.0
Oxytropis serecia	4/18-5/16	5/2	10.1	6/6-7/3	6/20	9.0	7/2-7/19	7/9	5.1	7/16-8/18	8/4	8.5	8/11-9/30	9/6	20.3
Commandra umbellata	4/28-5/25	5/10	9.6	6/4-6/28	6/21	7.0	6/28-7/18	7/9	6.4	—	—	—	9/6-10/10	9/22	10.4
Zygadenus venenosus	4/18-5/14	5/1	9.8	6/6-7/5	6/23	8.4	6/25-7/16	7/9	6.1	8/2-8/12	8/8	5.6	6/26-8/16	7/27	15.4
Pedicularis contorta	4/25-5/21	5/9	9.3	6/1-7/14	6/24	14.8	6/15-7/27	7/11	14.5	6/25-8/11	7/26	15.4	7/22-9/2	8/15	17.9
Lupinus serecius	5/10-6/2	5/21	7.3	6/18-7/5	6/28	6.5	7/12-7/30	7/23	7.2	8/1-8/18	8/6	5.9	8/12-9/8	8/29	10.4
Antennaria rosea	5/3-5/30	5/16	9.7	6/12-7/6	6/29	7.9	7/1-7/20	7/12	5.5	7/14-8/10	7/27	7.6	—	—	—
Achillea millefolium	4/28-5/18	5/6	7.5	6/23-7/15	7/6	8.1	7/21-8/10	8/1	7.0	8/11-9/6	8/30	7.6	8/16-9/27	9/2	11.8
Linum perenne	4/20-5/22	5/6	10.7	6/30-7/12	7/6	4.5	7/16-8/5	7/25	6.8	7/22-8/19	8/10	9.0	8/26-10/2	9/16	12.4
Galium boreale	5/7-5/24	5/15	7.2	7/8-7/18	7/11	3.3	7/28-8/14	7/31	5.5	8/6-9/8	8/20	9.3	8/23-9/18	9/5	9.2
Gaillardia aristata	5/3-5/28	5/17	8.9	7/11-7/22	7/15	3.8	7/18-8/12	8/1	6.4	8/11-9/3	8/23	7.2	8/20-9/24	9/6	11.9
Campanula rotundifolia	4/24-6/6	5/8	13.3	7/12-7/24	7/17	4.1	7/26-8/13	8/4	6.2	8/6-8/28	8/17	6.6	8/14-9/28	9/4	14.1

Table 7.—*Range, mean, and standard deviation (s) of phenological event dates for prominent forbs on a mountain grassland with a northeast exposure at 7,100 ft (2 164 m) elevation over a 10-year period*

Species	Growth starts			First bloom			Blooming over			Dissemination starts			Plant dried		
	Range	Mean	s	Range	Mean	s	Range	Mean	s	Range	Mean	s	Range	Mean	s
			Days			Days			Days			Days			Days
Lomatium cous	4/23–5/20	5/7	10.0	5/2–6/3	5/18	11.7	6/1–7/5	6/19	10.4	6/28–7/26	7/14	7.0	7/12–7/30	7/19	5.9
Anemone patens	4/27–5/22	5/9	9.6	4/30–6/2	5/18	10.3	5/15–6/13	6/3	9.6	6/20–7/20	7/7	8.4	8/18–9/19	8/30	8.7
Fritillaria pudica	4/23–5/20	5/8	10.0	5/6–5/29	5/19	8.0	5/22–6/16	6/7	9.2	7/13–8/1	7/23	6.4	7/10–8/3	7/24	7.1
Dodecatheon conjugens	4/24–5/22	5/9	10.4	5/8–6/4	5/26	8.4	5/30–6/30	6/16	9.6	7/9–7/24	7/16	4.8	7/15–7/28	7/19	5.3
Saxifraga montanensis	4/24–5/22	5/8	11.6	5/15–6/8	6/2	7.8	6/5–7/1	6/19	9.3	6/20–7/27	7/9	10.0	7/10–8/5	7/23	9.0
Agoseris glauca	4/27–5/22	5/10	10.7	5/15–6/13	6/3	8.3	6/5–6/25	6/14	10.0	6/9–7/10	7/1	9.2	6/22–9/25	7/20	25.4
Viola adunca	4/28–5/28	5/14	10.8	5/22–6/22	6/8	10.5	6/5–7/9	6/26	10.4	7/12–8/2	7/24	8.1	8/4–9/22	9/11	14.3
Myositis sylvatica	4/27–5/23	5/11	9.9	5/23–6/20	6/10	10.2	6/14–7/14	7/5	8.8	7/5–7/18	7/12	4.8	7/6–8/10	7/23	10.5
Geum triflorum	4/25–5/20	5/8	10.4	5/30–6/19	6/12	7.3	6/12–7/5	6/28	7.3	7/13–8/1	7/23	6.5	8/20–10/7	9/13	16.3
Delphinium bicolor	4/27–5/23	5/10	10.1	5/28–6/27	6/15	9.8	6/12–7/21	7/3	11.7	7/6–7/24	7/14	6.0	7/4–8/5	7/18	8.5
Cerastium arvense	4/28–5/23	5/10	10.3	6/2–6/30	6/19	9.9	6/28–7/15	7/8	6.4	7/9–7/27	7/18	4.5	7/30–9/10	8/20	11.6
Polygonum bistortoides	4/26–5/22	5/9	10.1	6/5–6/30	6/19	7.4	7/1–7/16	7/10	6.6	7/7–7/23	7/15	4.8	7/18–8/7	7/29	5.8
Phlox multiflora	4/28–5/23	5/12	9.3	6/5–7/5	6/20	9.6	6/30–7/19	7/11	7.2	7/18–8/12	8/3	8.3	8/20–10/3	9/15	12.4
Oxytropis sericea	4/26–6/2	5/13	11.2	6/10–7/9	6/27	9.0	6/30–7/24	7/13	8.6	7/31–8/24	8/10	7.1	8/20–9/28	9/17	11.8
Zygadenus venenosus	4/26–5/21	5/9	10.4	6/18–7/11	7/2	5.9	7/9–7/19	7/13	3.8	7/28–8/18	8/11	6.5	7/14–8/18	8/5	10.9
Antennaria rosea	5/6–6/5	5/24	10.6	6/17–7/13	7/3	8.7	6/30–7/26	7/17	7.2	7/22–8/9	7/31	5.7	—	—	—
Lupinus sericeus	5/10–6/7	5/28	8.7	6/24–7/13	7/4	6.5	7/12–8/2	7/22	7.6	7/15–8/12	8/4	8.4	8/13–9/15	8/30	12.0
Achillea millefolium	4/28–5/28	5/13	10.9	6/30–7/13	7/10	5.0	7/29–8/23	8/6	8.2	8/8–9/10	8/27	10.7	7/26–9/20	8/30	16.7
Linum perenne	4/28–5/25	5/13	10.0	7/3–7/16	7/11	4.5	7/16–8/4	7/27	6.7	7/26–8/30	8/16	9.7	9/13–10/10	9/27	7.8
Galium boreale	5/6–6/3	5/19	9.1	7/11–7/22	7/16	3.8	7/22–8/16	8/1	5.1	—	—	—	8/20–9/18	9/7	10.6
Gaillardia aristata	5/10–6/10	5/26	9.6	7/15–7/24	7/16	3.3	7/24–8/12	8/3	5.6	8/14–9/10	8/28	9.2	8/26–9/25	9/9	10.8
Campanula rotundifolia	4/26–5/26	5/12	11.2	7/17–7/22	7/19	1.6	7/31–8/16	8/6	5.2	8/12–9/4	8/22	6.8	8/19–9/14	9/4	8.0
Erigeron subtrinervis	5/4–6/1	5/18	9.4	7/20–7/27	7/23	2.9	7/30–8/26	8/14	8.8	8/15–9/6	8/29	7.4	9/4–10/5	9/21	9.2

Table 8.—*Range, mean, and standard deviation (s) of phenological event dates for prominent grasses on southwest and northeast exposures at 7,100 ft (2 164 m) elevation over a 10-year period*

Species	Growth starts			First bloom			Blooming over			Dissemination starts			Plant dried		
	Range	Mean	s	Range	Mean	s	Range	Mean	s	Range	Mean	s	Range	Mean	s
			Days			Days			Days			Days			Days
SOUTHWEST EXPOSURE															
Danthonia intermedia	4/28–5/24	5/12	10.2	6/10–7/4	6/25	7.8	6/29–7/20	7/9	6.2	7/22–8/10	7/30	6.3	8/18–10/15	9/25	17.4
Festuca idahoensis	4/21–5/16	5/4	10.0	5/22–6/30	6/14	13.2	7/6–7/26	7/13	4.1	7/25–8/17	8/5	6.2	8/27–10/15	9/21	16.8
Stipa occidentalis	4/28–5/28	5/10	10.8	6/1–7/5	6/24	10.6	7/13–7/24	7/18	3.5	7/21–8/15	8/7	8.0	8/30–10/20	9/20	16.6
Agropyron spicatum	4/25–5/18	5/6	8.3	6/1–7/3	6/22	9.5	7/12–7/25	7/19	3.6	8/16–8/23	8/19[1]	3.8	9/6–10/7	9/22	8.9
NORTHEAST EXPOSURE															
Danthonia intermedia	4/28–5/29	5/16	11.9	6/8–7/8	6/27	10.0	7/1–7/21	7/13	7.3	7/26–8/12	8/3	6.1	9/10–11/2	10/6	13.6
Festuca idahoensis	4/25–5/23	5/8	11.1	5/24–6/29	6/17	12.4	7/3–7/24	7/16	6.2	7/28–8/21	8/11	7.2	8/25–11/1	10/7	18.0
Stipa occidentalis	4/29–5/29	5/17	9.5	7/1–7/12	7/7	4.0	7/17–7/27	7/22	3.1	7/26–8/18	8/10	7.4	9/2–10/20	9/25	14.4
Agropyron caninum	5/1–5/30	5/16	11.6	6/10–7/15	6/29	12.2	7/9–7/29	7/22	5.3	8/17–8/28	8/24	3.7	8/27–10/6	9/19	11.8
Agropyron spicatum	5/1–5/28	5/14	9.7	6/12–7/8	6/25	8.3	7/16–7/29	7/23	3.9	—	—[1]	—	9/4–10/5	9/22	10.0
Bromus anomalus	4/28–5/28	5/16	10.8	6/23–7/9	7/1	5.1	7/20–7/29	7/26	2.7	8/18–9/2	8/25	4.5	8/30–10/12	9/22	13.5

[1]Maturing seed usually destroyed by insects.

date. The seed-ripe stage for grasses generally can be expected to occur in 2 out of 3 years within about 6 days of the average date.

Those forbs that tended to bloom early in the season also tended to dry early, with the exception of the apparently deeply rooted *Anemone patens* which tended to dry fairly late. With *Anemone patens* excluded, the average drying date of the early blooming species preceded that of the late bloomers by about 7 weeks. The grasses were generally the last to dry, averaging about 2 weeks later than the late forbs. Growth activities with some forbs virtually ceased once the seed had matured and began dissemination. Other species continued to remain green and photosynthetically active for up to 2 months following the seed-ripe stage. *Dodecatheon conjugens, Fritillaria pudica, Delphinium bicolor,* and *Zigadenus venenosus* typified those species that ceased growth activity with the production of seed. *Geum triflorum, Linum perenne, Viola adunca, Anemone patens,* as well as most grasses, continued with a substantial period of growth following seed production. Although some species tended to dry earlier on the southwest than on the northeast exposure, others did not; the average difference between exposures was not significant because of this variability between species. Earlier I found that the forbs on these grasslands dried an average 18 days later and the grasses 10 days later at sites 1,100 ft (335 m) higher in elevation (Mueggler 1972a).

The between-year variation in the date of drying amounted to as much as 6 to 8 weeks for some species (*Agoseris glauca, Achillea millefolium, Danthonia intermedia, Festuca idahoensis*), and as little as 3 weeks for others (*Saxifraga montanensis* and *Polygonum bistortoides*). Except for those forbs that tended to dry early in the season upon completion of seed production, the drying date appeared to be controlled primarily by the availability of soil moisture adequate for growth. Generally, the forbs and grasses on these mountain grasslands can be expected to dry in 2 out of 3 years within about 12 days of their mean drying date.

Although most species apparently became dormant for the remainder of the year following drying, several produced new leaves again in the fall in some years. This regrowth occurred most regularly with *Geum triflorum, Saxifraga montanensis,* and *Cerastium arvense,* and to a lesser degree with the grasses. Fall regrowth in *Geum triflorum* and *Saxifraga montanensis* was in the form of a small rosette of new leaves within the outer rosette of dried leaves. Regrowth of *Cerastium arvense* was in the form of small leaves in the axils of dried leaves distributed along the stems.

The duration of growth, that span of time between the start of growth and when the plants dried, differed appreciably between species. On these 7,100-ft (2 164-m) elevation sites, the mean duration of growth over the 10-year period varied from 60 to 150 days. The following forbs completed their growth cycle in less than 80 days: *Agoseris glauca, Delphinium bicolor, Dodecatheon conjugens, Fritillaria pudica, Lomatium cous, Myosotis sylvatica,* and *Saxifraga montanensis.* Those forbs that remained active on the average an excess of 115 days were: *Campanula rotundifolia, Comandra umbellata, Erigeron subtrinervis, Geum triflorum, Linum perenne, Oxytropis serecia,* and *Viola adunca.* The grasses generally remained photosynthetically active for a considerably longer period (125 to 150 days) than most of the forbs.

Although duration of growth varied appreciably among both species and years, it did not differ significantly between exposures. Duration of growth was generally about 1 week shorter at 8,200 ft (2 500 m) than at 7,100 ft (2 164 m) elevation (Mueggler 1972a). For species common to both elevations, the growth period averaged 94 days at 8,200 ft (2 500 m) and 103 days at 7,100 ft (2 164 m) over a 5-year period.

Relation of Seasonal Development to Weather

Blaisdell (1958) concluded that high temperatures hasten at least the early phases of plant development. For example, he found a significant negative correlation between March-April mean temperature and the dates of the appearance of flower stalks for eight native perennial species on sagebrush-grass rangelands ($r = -0.62^{*}$), and between March-May mean temperature and the dates of full bloom ($r = -0.93^{**}$). On the other hand, he found that development during the latter part of the growing season apparently was most closely related to precipitation; for example, the dates that plants dried in his study were positively correlated with April-May precipitation ($r=0.82^{**}$). Costello and Price (1939) determined that above normal, evenly distributed rainfall during the summer extended the period required for the ripening of seed on mountain herblands.

Seven weather variables expected to affect development rate were selected to examine the relation between weather and phasic development on mountain grasslands: May heat-sum, May-June heat-sum, heat-sum to first bloom, June precipitation, May-June precipitation, July 1 soil moisture, August 1 soil moisture. Heat-sum (degree-days) was computed by averaging the maximum and minimum air temperatures daily and accumulating the number of degrees this average exceeded 5° C. The 5° C critical level was selected because Larcher (1980) maintains that, as a rule, terrestrial vascular plants are active in the production of dry matter and growth only between 5° C and 40° C.

Weather was not monitored sufficiently in advance of the start of growth to permit determining what factors related to this stage. Obvious growth activity usually began shortly after snowmelt. The start of growth for some plants was uncertain, however, because small green leaves were frequently present at the time of snowmelt. These either began growth under the winter snowpack, or more likely overwintered from fall regrowth. Most conspicuous among these species were *Saxifraga montanensis* and *Geum triflorum,* and occasionally *Festuca idahoensis* and *Agropyron spicatum.* Mooney and Billings (1960) observed that the alpine species *Saxifraga rhomboidea, Geum rossii,* and *Polygonum bistortoides* frequently began growth under the snow.

The day of the year that flower stalks in *Festuca idahoensis* and *Agropyron spicatum* appeared was significantly negatively correlated with both May and May-June heat-sums. These correlation coefficients ranged between −0.63 and −0.75. in other words, the warmer the May and June temperatures, the sooner flower stalks appeared, which supports the findings of Blaisdell (1958).

Flowering date also was closely associated with either May or May-June heat-sums. Of the 16 species tested, 11 were correlated significantly with these temperature measures. Almost all correlation coefficients regardless of statistical significance were negative, suggesting that warmer May and June temperatures speeded up the flowering process. The significant correlation coefficients ranged from −0.64 for the *Myositis sylvatica*/May heat-sum to −0.85 for the *Festuca idahoensis*/May heat-sum. Cumulative degree-days until first bloom lacked consistency between years for any given species. The coefficient of variations for degree-days until first bloom ranged from approximately 15 percent for late blooming species to approximately 75 percent for early bloomers. This suggests either that flowering of these species is not rigidly dependent upon cumulative degree-days, or that the heat-sum measure used was inadequate to detect this dependency.

Seed ripening was significantly correlated with weather in only 5 of the 16 species tested. Most of these relationships were again with May heat-sums. The correlation coefficients were negative as they were with flowering. Since seed ripening of the species involved usually did not occur until at least early July and since flowering of most of these same species was significantly correlated with May heat-sum, the significant correlation between May heat-sum and ripening very likely results from a high correlation between flowering and seed maturation. *Gaillardia aristata* and *Phlox multiflora*, both relatively late maturing, were the only species where seed ripening was significantly correlated with May-June precipitation ($r = 0.68$ and 0.71 respectively). These two species delayed maturation in years with greater than average precipitation in May and June.

CONCLUSIONS AND IMPLICATIONS

While average forage production on native rangelands sets the average stocking rate, yearly variation in production determines annual adjustments in stocking that may be required. This study indicates that total herbage production on mountain grassland ranges can be expected to fall within 85 to 90 percent of the long-term mean in 2 out of 3 years. The yearly variability in production of vegetation classes and of individual species is considerably greater. If stocking depends primarily upon the amount of grasses, forage production can be expected to fall within approximately 75 percent of the long-term mean two-thirds of the time; however, if forbs are the primary forage source, forage production can be expected to be within 80 to 85 percent of the mean in 2 out of 3 years. Production of individual species can be expected to be within only 33 to 76 percent of long-term means in 2 out of 3 years, depending upon the species. A "good" year for production of grasses is neither a good nor a poor year for forb production on these mountain grasslands. Species apparently react differently to subtle differences in weather. Increased yields of one often compensate for decreased yields of another and thus reduce yearly differences in total production. Although northerly exposures are generally more productive than southerly exposures, the relative amount of yearly variation in production is similar.

Although over 88 percent of the year-to-year variation in production of vegetation classes and of abundant species on the study site was accounted for by models incorporating only three weather parameters, applying such models beyond the immediate site can be hazardous. Models developed for one exposure seldom performed well on the opposing exposure for the same vegetation classes and species, even though the vegetation and many environmental characteristics were fairly similar. One cannot, therefore, assume without further testing that a model suitable for predicting production at one location on mountain rangelands will be applicable to other similar locations.

On these short-season, mountain grasslands a negative relationship may exist between fall regrowth of *Agropyron spicatum* and *Festuca idahoensis* and production the following year. Verification of this relationship should improve predictions of the annual production of these important forage species.

Vegetation begins growth sooner and develops more rapidly in some years than in others. Because date of range readiness for grazing depends upon how rapidly the vegetation develops, the extent of such variation is important to those managers responsible for fixing grazing seasons. In 2 out of 3 years, most mountain grassland species in southwestern Montana can be expected to begin growth within 8 to 12 days of their respective average date for the beginning of growth. Growth usually begins about 1 week later on northerly than on southerly exposures. In 2 out of 3 years, those species that flower early in the season can be expected to bloom within 10 days of their mean flowering date, and those that flower late in the season can be expected to be within 4 to 6 days of their mean date. Flowering generally occurs about 1 week later on northerly than on southerly exposures. From 1 to 2 months usually elapses from the time a species first begins to bloom and when seed begins to disseminate. Two-thirds of the time seed dissemination for most forbs occur within 8 days and for the grasses within 6 days of the average date for each species. Some species dry about 2 months later in some years than in others; generally, however, in 2 out of 3 years the vegetation can be expected to dry within 12 days of the long-term mean date for drying.

Range managers generally rely upon vegetation and soil readiness indicators to decide when grazing can safely begin in the spring or early summer. *Delphinium bicolor* in full bloom and the appearance of *Festuca idahoensis* flower stalks are used as indicators of grazing readiness on mountain grasslands in Montana (U.S. Dept. Agric., Forest Service 1969). Applying these indicators suggests that the date of range readiness can differ as much as 5 weeks over a 10-year

period on these mountain grasslands. In 2 out of 3 years, however, the vegetation on these grasslands should be ready to graze within 2 weeks of the average date of readiness.

Early growth stages, such as the appearance of flower stalks and blooming, appear to be associated with May and June temperatures. As might be expected, warm temperatures speed up these early development stages, and consequently speed up the date of range readiness for grazing.

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Yearly differences in plant development and herbage production of prominent species within the *Festuca idahoensis/Agropyron spicatum* habitat type are documented for a 10-year period. Differences between northeast and southwest exposures at an elevation of 7,100 ft (2 164 m) are discussed. Data are expressed as ranges, means, and standard deviations. Correlation coefficients between production and major weather variables are given, and multiple regression models for predicting production from weather variables are presented.

KEYWORDS: production, seasonal development, phenology, weather effects, variability, mountain grasslands, Montana

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Costs for Developed Recreation Sites in the Northern Region, USDA Forest Service

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RESEARCH SUMMARY

Increasingly restrictive budgets, coupled with the information needs of quantitative forest planning models, compel managers to be more concerned with the costs of providing developed recreation opportunities in the Northern Region. The research being reported here studied 259 sites, almost half of those existing in 1980. Data were obtained from a variety of sources—personal interviews, facility inventory records, accounting records, and more. Estimates were made for planning costs, construction costs, and operation and maintenance costs. Costs that did not occur annually were annualized (amortized) at 4 and 7 percent real discount rates.

On an annualized basis (discounted at 4 percent), major interpretive sites are the most costly in the Northern Region, with an average annualized cost of about $360 per PAOT (**P**erson **A**t **O**ne **T**ime); annual costs for observation sites are least costly, averaging about $38 per PAOT. Annualized costs for other types of recreation sites are provided on the basis of the experience level for which they were designed. Information is presented to convert costs per PAOT to a site and recreation use level basis. For example, the annualized cost per major interpretive site is about $53,000. Finally, cost estimation equations are presented. Each permits estimation of total annualized costs per site as a function of PAOT capacity, and remoteness or fee payment where appropriate.

Costs for Developed Recreation Sites in the Northern Region, USDA Forest Service

Ervin G. Schuster
Kenneth C. Gibbs

INTRODUCTION

The decade of the 1970's reflected a substantial increase in demand for outdoor recreation. Overall recreation activity levels on National Forests in the Northern Region increased by about 25 percent. The nearly identical increase in developed outdoor recreation was met with an 18-percent increase in National Forest land allocated to developed recreation. Facilities such as campgrounds, picnic and boating sites (fig. 1), and interpretive facilities were constructed, operated, and maintained for public use.

Figure 1.—Excursion boat docking at Meriwether Campground, Holter Lake, Helena National Forest

The foreseeable future closely reflects the past. Agency budgets for recreation-related activities are not expected to increase sharply. Recent midlevel projections (USDA Forest Service 1980) of outdoor recreation demand to the year 2000 show an expected increase of 33 percent in developed camping over 1977, a 24-percent increase for picnicking, and a 34-percent increase for water-based outdoor recreation. The challenge is to do more, provide more, probably with less. Only an efficient operation can do this. Costs must be carefully weighed against benefits.

Pressures of high energy costs, restrictive budgets, and administrative accountability have caused managers to seek greater efficiency and cost effectiveness in resource usage. The 1974 Resources Planning Act requires identification of costs and benefits associated with Forest Service management actions. The National Forest Management Act of 1976 further reinforces the need to identify costs for land management planning. The information needs of quantitative forest planning models, such as FORPLAN, focus attention on costs. Yet very little information is available on costs.

The study being reported here was designed to provide recreation managers within the USDA Forest Service Northern Region with estimates of current costs for developed recreation sites and statistical models to predict costs in the future. Certain of these results can also contribute to management of dispersed recreation areas. This report is a substantial condensation of the study and its results. Readers interested in complete results and more detailed information are referred to a publication by Gibbs and Reed (1983).

METHODS

Developed recreation activities are those taking place at sites that have been "modified to enhance recreation opportunities," consistent with the natural resources present (USDA Forest Service 1982). The level of modification is related to the experience level (EL) expected for the recreationist:

Site modification	EL	User experience
Minimal modification	1	Primitive solitude
Little modification	2	Near primitive
Moderate modification	3	Essentially natural
Heavily modified	4	Not necessarily natural
Most modification	5	Social, group interaction

Clearly, there is a near-continuum between dispersed and developed recreation, with the latter characterizing the higher experience levels. Formal sites are commonly associated with developed recreation. The following types of recreation sites listed below were identified for study:

—Campgrounds
—Picnic grounds
—Boating sites
—Swimming sites
—Interpretive sites
—Observation sites
—Documentary sites

These types of sites, together with the EL classification, constitute the specific focuses for cost estimation.

Cost estimates for each type of recreation site were based on the total of planning costs and construction costs, together with operation and maintenance costs. Planning costs consist of labor expenses for time spent by personnel in design and layout activities, prior to facility construction. The result is an approved site development plan. Costs associated with site selection or review and approval of plans were not measured. Construction costs include purchase, installation, and construction of facilities—equipment, structures, etc.—at the site. Operation and maintenance costs are those annually recurring expenses needed to maintain a facility in operating order during a season, such as personnel, utilities, tools, and materials. Several costs were not assessed: administrative overhead, external (third-party) costs, and land opportunity costs.

We attempted to estimate costs of developed recreation sites for use in project evaluations and annual budgeting. Project evaluations frequently compare annual benefits to annual costs over the expected life of the project. But neither planning costs nor construction costs occur annually; at any site, they occur over a brief time period and then cease to exist. These costs were estimated and then converted (amortized) to an annualized equivalent by means of an installment payment formula. We used 4- and 7-percent real discount rates. Amortization periods varied, planning costs over 20 years and construction costs over 10 or 20 years on an item-by-item basis. Operation and maintenance costs were not amortized since they are already on an annual basis. For annual budgeting purposes, unannualized planning costs and construction costs are appropriate.

Because there are so many developed recreation sites in the Northern Region, estimates of cost parameters had to be developed by means of sample-based estimators. A sampling frame was developed, consisting of the 557 sites existing in 1980. Sampling frame of approximately one-third, one-half, or 100 percent resulted in the actual sample distribution shown in table 1. In total, 259 sites were evaluated, about 47 percent of the population. The sample was distributed over northern Idaho, western Montana, and eastern Montana.

A variety of information sources were used to estimate costs. Data on planning costs were obtained by interviewing personnel in the Northern Region. Construction cost estimates adopted the "current replacement value" convention (rather than original cost or some other convention). An inventory listing all facilities at each sampled site was obtained from RIM Facility Condition Records. Replacement cost estimates were generally obtained from RIM Special Report No. 31, although several alternative information sources were used as well. Almost all data used to measure operation and maintenance costs were obtained through interviews with recreation managers at sampled Ranger Districts. A questionnaire format was used. Supporting records (such as project work plans, vehicle use records, contracts, project managers' statements, and utility bills) were accessed during the interviews.

Table 1.—Study population and sample totals, by type of recreation site, Northern Region, 1980

Type of recreation site	EL[1]	Region total	Sites sampled
Family campground	2	72	40
	3	258	93
	4	14	14
Family picnic grounds	2	10	9
	3	63	30
	4	6	6
Boating sites	All	60	27
Swimming sites	All	19	9
Group campgrounds	All	3	3
Group picnic grounds	All	13	7
Interpretive sites, major	All	3	3
Interpretive sites, minor	All	17	9
Observation sites	All	10	6
Documentary sites	All	8	3
Information sites	All	1	0
Total		557	259

[1]Experience level.

RESULTS

Three types of study results will be presented. First, average costs for the various types of recreation will be discussed. The planning costs and construction costs are presented in both annualized and unannualized form. The annualized form of those costs, together with annual operation and maintenance costs, constitutes the estimate of average annual costs. Second, a set of multipliers is presented to convert average costs based on site capacity to either a site or output basis. Finally, a set of cost estimation equations is presented, each of which estimates average annual total costs per site on the basis of site capacity.

Average Costs

The information contained in table 2 provides an overall summary of the cost estimates developed in this study. All costs are expressed in terms of average costs per unit of site capacity. Capacity is measured by PAOT (Persons At One Time), a measurement unit common to all Forest Service developed recreation sites. PAOT represents the number of people who could simultaneously recreate at a site according to its design and facilities. Additionally, all dollars are expressed at the 1980 price level. The total average cost consists of the sum of the appropriate average cost components. For example, the total annual cost for EL 2 family campgrounds annualized at 4 percent is $130.33 per PAOT ($1.61 + $66.63 + $62.09).

The total of the average costs per PAOT varies widely. The least expensive facilities are observation sites and group campgrounds. The most costly facilities are

Table 2.—Average cost (dollars) per PAOT for developed recreation in the Northern Region, by type of recreation site, annualized and unannualized, 1980

Type of recreation site	EL[1]	Unannualized costs[2]		Annualized costs				Annual operation and maintenance[5]	Total Annualized		Unannualized
		Planning	Construction	Planning[3]		Construction[4]					
				4	7	4	7				
Family campgrounds	2	21.88	824.21	1.61	2.07	66.63	83.87	62.09	130.33	147.53	908.18
	3	19.89	922.42	1.46	1.88	73.26	92.07	48.34	123.06	142.29	990.65
	4	18.20	1,101.17	1.34	1.72	86.69	109.19	40.51	128.54	151.42	1,159.88
Family picnic grounds	2	10.00	1,116.15	[illegible]	94	85.98	108.91	50.54	137.26	160.39	1,176.69
	3	14.49	773.05	1.07	1.37	61.86	77.59	41.17	104.10	120.13	828.71
	4	14.04	716.62	1.03	1.33	55.87	70.55	28.96	85.86	100.84	759.62
Boating sites	All	13.84	627.86	1.02	1.31	46.62	59.65	15.79	63.43	76.75	657.49
Swimming sites	All	16.42	549.23	1.21	1.55	41.82	53.14	19.85	62.88	74.54	585.50
Group campgrounds	All	16.36	244.01	1.20	1.54	18.64	23.67	20.24	40.08	45.45	280.61
Group picnic grounds	All	9.99	687.71	.73	.94	53.51	67.61	29.08	83.32	97.63	726.78
Interpretive sites, major	All	38.73	2,512.92	2.85	3.66	186.76	238.91	170.09	359.70	412.66	2,721.74
Interpretive sites, minor	All	6.81	1,986.24	[illegible]	.64	148.06	189.24	16.46	165.02	206.34	2,009.51
Observation sites	All	5.96	299.31	[illegible]	[illegible]	23.40	29.52	13.96	37.80	44.04	319.23
Documentary sites	All	15.26	920.49	1.12	1.44	70.60	89.54	31.18	102.90	122.16	966.93

[1]Experience level.
[2]Unannualized costs are not the same as amortizing at a 0-percent discount rate.
[3]Amortized over 20-year project life.
[4]Individual facility items amortized over 10- or 20-year project life, depending on the item.
[5]Operation and maintenance costs are average annual costs.

interpretive sites, whether major or minor. But these extremes are represented by vastly different facilities. The larger PAOT capacity of group campgrounds tends to drive down average costs. And once established, observation sites are almost self-administering. On the other hand, interpretive sites are very labor-intensive facilities. In particular, major sites are typically highly developed, and usually include a separate building where environmental awareness and other educational programs are conducted.

Attention focused on cost extremes is somewhat misleading. Although the cost per PAOT may be high or low, there are very few extreme-cost facilities in the Northern Region. For example, there are only three facilities each in the group campground and major interpretive site categories. The bulk of the developed recreation sites are family campgrounds (EL 2 and 3) and family picnic grounds (EL 3). They constitute over 70 percent of the developed recreation sites. Tending toward the middle of the costs per PAOT, it would be correct to conclude that these three types of sites incur the bulk of the total costs.

It is difficult to reach unequivical conclusions about which type of cost is most significant—planning, construction, or operation and maintenance. The conclusion depends on both the type of recreation site and whether amortized or unamortized costs are assessed. But most evaluations would conclude that planning costs are relatively insignificant, being totally overwhelmed by the other costs. Comparisons between construction costs and operation and maintenance costs are less clear. Inspection of unamortized costs shows that construction costs exceed those for operation and maintenance by a factor as little as 12 for group campgrounds to as much as 121 for minor interpretive sites. When the comparison is made between annual operation and maintenance and annualized construction costs, the gap shrinks to as little as a factor of about 2. In fact, average operation and maintenance costs exceed construction costs for group campgrounds when the latter is annualized with a 4-percent real discount rate. The aforementioned vagueness notwithstanding, study results do support the overall conclusion that planning costs are least significant, followed by operation and maintenance costs, and finally the construction costs, with the latter being appreciably larger if not annualized.

Unlike the planning cost or the construction cost categories, operation and maintenance cost data were collected for specific subcategories. These are presented as percentage distributions in table 3 for the three most common types of developed recreation sites in the Northern Region. Labor costs clearly dominate operation and maintenance costs. Utility costs are inconsequential. Labor costs included permanent and temporary personnel as well as contributed personnel (YACC, CETA, Job Corps) and borrowed fire and timber crews. As shown, contributed and borrowed labor account for 12 to 18 percent of all operation and maintenance costs, about 25 percent of all labor costs. The percentage distribution pattern of operation and maintenance costs for other types of recreation is very similar to those shown in table 3.

Table 3.—Percentage distribution of operation and maintenance costs for the types of developed recreation facilities, by cost subcategories

Cost subcategory	Family campgrounds		EL 3, family picnic ground
	EL 2[1]	EL 3	
Labor	62	64	54
—contributed/borrowed	(18)	(17)	(12)
—Forest Service	(44)	(47)	(42)
Contract	15	16	24
Vehicles	14	12	13
Utilities	—	—	—
Tools and materials	9	8	9
Total	100	100	100

[1]EL = experience level.

Cost Estimate Conversions

Average costs can be expressed on bases other than PAOT. Two common, alternative bases are site and RVD. A site refers to the overall campground or picnic ground itself and not to a family unit or camping site within the campground. The Recreation Visitor Day (RVD) is an output measure, reflecting use by recreationists at a site. An RVD represents 12 visitor hours spent in any recreation activity; the hours may be aggregated continuously, intermittently, or simultaneously, by one or more persons. Table 4 is provided to the reader desiring cost estimates in terms of dollars per site or RVD. It consists of a set of multiplication factors, and is to be used in conjunction with table 2. For example, assume the need to estimate average annual cost per RVD, amortized at 4 percent, for EL 2 family campgrounds. Simply locate the appropriate cost per PAOT in table 2 ($130.33) and the conversion factor in table 4 (0.01265). Multiplying the cost per PAOT by the factor results in a cost in 1980 dollars per RVD of $1.65 ($130.33 X 0.01265). Similarly the annual average cost per site is $3,063 ($130.33 X 23.50).

Cost Prediction Models

Finally, this study attempted to develop models to predict the annual total costs (AnTC) of the several recreation activities studied. Results of this effort are shown in the equations of table 5, which explain the variation in AnTC on the basis of site capacity and other site-specific variables. The models shown are the final models, not the initial ones. Some initial models contained additional independent variables: G—geographic zone and L—length of season. But in the model-form selected, only those variables shown in table 5 were statistically significant at the $\alpha = 0.05$ level. The intermediate models treated types of recreation sites and experience level as dummy variables and contained interaction terms; they were judged too cumbersome for general presentation. The final models shown in table 5 are a condensation of the intermediate models. Annual total costs consist of annual operation and maintenance costs together with planning costs and facilities costs annualized with a 4-percent discount rate. Final models contain three independent variables—site capacity (PAOT), remoteness (R), and fee structure (F). The fee variable refers to charges to users of a site. The variable is code "1" if fees are charged, "0" if not.

Cost prediction models can be used directly to estimate annual total costs. Information needed includes specification of PAOT site capacity, the remoteness variable R—distance in miles to the nearest Federal highway or interstate freeway, and, in some cases, existence of user fees. Specified PAOT levels and remoteness distances should be within the data range shown. For example, an estimate of the annual total cost of an EL 3 family picnic ground with a PAOT capacity of 100 located 10 miles (16.1 km) from the nearest Federal highway would be:

$$\begin{aligned} \text{AnTC} &= \$2{,}550 + \$35.27(100) + \$70(10) \\ &= \$2{,}550 + \$3{,}527 + \$700 \\ &= \$5{,}777 \end{aligned}$$

If the user wants to estimate AnTC for some hypothetical campground of unknown remoteness, the mean distance (R) for sample data of 20.6 miles (33.2 km) could be used.

Table 4.—Conversion factors to $/site and $/RVD from $/PAOT, by type of recreation site, Northern Region, 1980

Type of recreation site	EL[1]	Multiplication conversion factors	
		$/site	$/RVD (1980)
Family campgrounds	2	23.50	0.01265
	3	89.09	.01401
	4	169.33	.01448
Family picnic grounds	2	20.56	.01869
	3	54.47	.03447
	4	98.33	.02161
Boating sites	All	88.78	.04809
Swimming sites	All	78.33	.03653
Group campgrounds	All	150.00	.04736
Group picnic grounds	All	59.29	.04224
Interpretive sites, major	All	147.50	.01766
Interpretive sites, minor	All	102.14	.00887
Observation sites	All	70.83	.03455
Documentary sites	All	23.33	.02187

[1]Experience level.

Table 5.—Annual total cost (AnTC) per site for developed recreation site in the Northern Region, by type of recreation site, 1980[1]

Type of recreation site	EL[2]	Cost prediction model	PAOT range[3]	
			Min.	Max.
Family campgrounds[4]	2	$AnTC = -2152 + 113(PAOT) - 0.073(PAOT)^2 + 3536(F) + 90.5(R)$	10	85
	3	$AnTC = -975 + 113(PAOT) - 0.073(PAOT)^2 + 3536(F) + 90.5(R)$	15	430
	4	$AnTC = 721 + 113(PAOT) - 0.073(PAOT)^2 + 3536(F) + 90.5(R)$	15	345
Family picnic grounds[5]	2	$AnTC = 335 + 35.27(PAOT) + 70(R)$	15	25
	3	$AnTC = 2550 + 35.27(PAOT) + 70(R)$	25	136
	4	$AnTC = 4941 + 35.27(PAOT) + 70(R)$	30	160
Boating sites	All	$AnTC = -1162 + 55.67(PAOT) + 70.13(R)$	20	250
Swimming sites	All	$AnTC = -1162 + 57.06(PAOT) + 70.13(R)$	20	200
Group picnic grounds	All	$AnTC = -1162 + 94.77(PAOT) + 70.13(R)$	32	490
Interpretive sites,[6] major	All	$AnTC = 30479 + 161.47(PAOT)$	120	175
Interpretive sites, other	All	$AnTC = -2187 + 161.47(PAOT)$	10	415

[1]Annual total costs consist of annual operation and maintenance costs, with planning costs and construction costs amortized at 4 percent.
[2]Experience level.
[3]The range for the remoteness variable (R) was 0 to 74 miles
[4]The general model estimating campgrounds had an $R^2 = 0.78$.
[5]The general model estimating picnic grounds, boating sites, and swimming sites had an $R^2 = 0.74$.
[6]The general model estimating interpretive sites had an $R^2 = 0.83$.

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MANAGEMENT APPLICATION

The cost information presented in this report has a variety of potential applications. The most obvious application involves the need for unit cost estimates in forest planning models, such as FORPLAN. Cost data contained in table 2, modified as needed by the conversion factors in table 4, are well suited to that use. The cost equations shown in table 5 lend themselves to economic efficiency analysis. Specifically, those equations can be used to identify the optimal capacity of recreation sites, be they campgrounds, picnic grounds, and the like. Finally, these data can prove useful when analyzing user fees or user benefits. In the case of fees, comparisons can be made between costs and revenues generated by fees with the possible outcome being fee structure modification. Where fee charges are not at issue, estimated costs can be compared to perceived user benefits in a subjective benefit-cost analysis.

Results presented have limitations. One limitation with this and similar studies is the accuracy of raw data. Data collection efforts were carefully planned, used best techniques available, and extended over several months. Nevertheless, data came from several sources, with varying degrees of accuracy. Data based on personal recall are always troublesome, although of minor importance on balance. Similarly, conversion factors for RVD-based cost estimates should be used with caution since the underlying RVD data are of unknown quality. Another limitation is that not all costs were measured. In particular, the absence of administrative overhead costs should be noted. These indirect costs are present but very difficult to measure and evaluate. Cost estimates presented necessarily understate the actual magnitude of costs.

PUBLICATIONS CITED

Gibbs, Kenneth C.; Reed, Frederick L. Estimation and analysis of costs for developed recreation sites in U.S. Forest Service Region One. Bulletin. Corvallis, OR: Oregon State University, School of Forestry, Forest Research Laboratory; 1983. In press.

U.S. Department of Agriculture, Forest Service. An assessment of the forest and rangeland situation in the United States. FS-345. Washington, DC: U.S. Department of Agriculture, Forest Service; 1980. 631 p.

U.S. Department of Agriculture, Forest Service. Forest Service Manual, Title 2300, Recreation Management. Washington, DC: U.S. Department of Agriculture, Forest Service; 1982: 2330.5.

Schuster, Ervin G.; Gibbs, Kenneth C. Costs for developed recreation sites in the Northern Region, USDA Forest Service. Res. Pap. INT-317. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 6 p.

Costs of various categories of campgrounds and picnic grounds, together with boating, swimming, and interpretive sites, are presented. Cost estimates are classified as to planning costs, construction costs, and operation and maintenance costs, all amortized and unamortized. Conversion factors are presented to express costs on the basis of site, site capacity, and recreation use levels. Statistical cost models are developed to predict annual total cost per site as a function of site capacity and other variables. Data were obtained for a sample of sites and converted to 1980 dollars.

KEYWORDS: costs, developed recreation, recreation management

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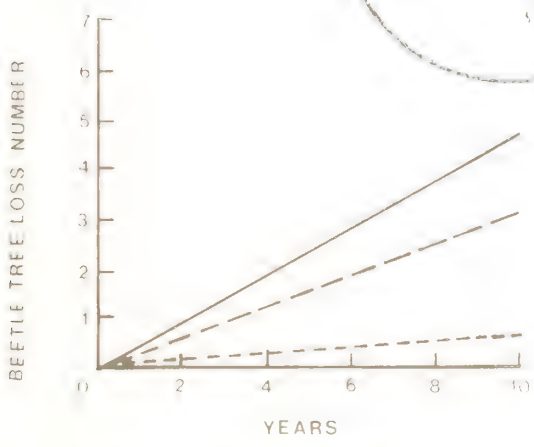
INT-318

September 1983

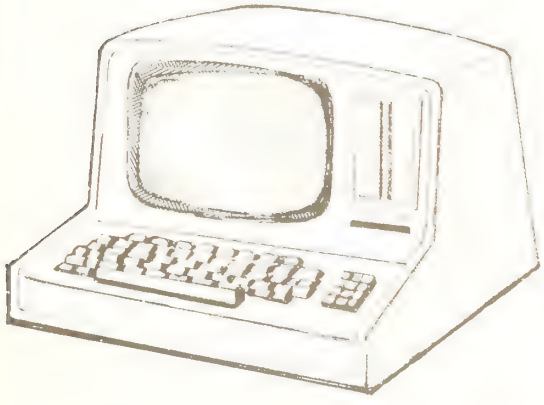
Estimating the Rate and Amount of Tree Loss from Mountain Pine Beetle Infestations

**Walter E. Cole
Mark D. McGregor**

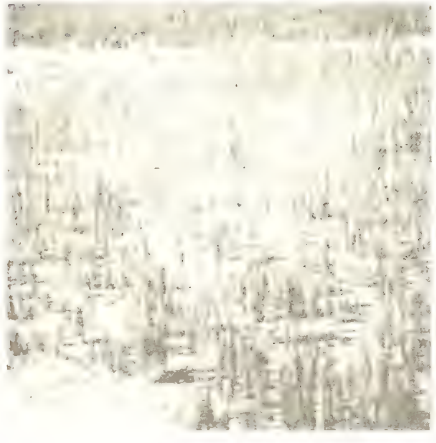
Outbreak-When?



Amount of Loss



Hazard Rating



Strategy or Prescription

THE AUTHORS

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RESEARCH SUMMARY

Because of recurrent depredations by the mountain pine beetle in lodgepole pine, managers have less than a 50 percent chance of growing lodgepole pine to 16-inch diameters in most stands. This paper describes a Rate of Loss Model that estimates the amount of tree and volume loss per year and the longevity of the infestation, and shows how the model can be incorporated into forest planning. The model assumes optimum conditions for the life of an epidemic. However, actual field conditions can cause beetle populations to deviate from predictions causing a bit of overestimation, which is not considered serious in most infestation cases.

The model predictions, based on 2-inch diameter classes as populations, are further modified by habitat type. The classification provides the framework essential for organizing information to select alternative management activities for habitat types. The Rate of Loss Model has been integrated with the Insect and Disease Damage Survey (INDIDS) models to estimate mortality trends for stands with ongoing mortality or to obtain loss estimates by diameter class over infestation time for green stands, should they become infested.

One approach to modeling tree mortality caused by the mountain pine beetle uses FORPLAN to predict susceptible areas within analysis areas, which one would be affected, and the expected mortality over two decades. Or, when stands within analysis areas are identified through timber or stand exam surveys, beetle attack may then be simulated by a "prescription" that shows the effects of an epidemic in the absence of timber management.

The model has been verified using some 2,500 stands in the Forest Service's Northern Region. By using assessments from FORPLAN and harvesting in high-hazard, susceptible stands before an epidemic develops, land managers should be able to minimize tree mortality caused by the beetle.

Estimating the Rate and Amount of Tree Loss from Mountain Pine Beetle Infestations

Walter E. Cole
Mark D. McGregor

INTRODUCTION

Because of recurrent depredations by the mountain pine beetle (*Dendroctonus ponderosae* Hopk.) in the Intermountain West, managers have less than a 50 percent chance of growing lodgepole pine to 16-inch (40.6-cm) diameters in most stands and, in some cases, less than 25 percent chance (Roe and Amman 1970). Consequently, forest managers commonly ask two questions: "Which of the lodgepole pine stands are most susceptible to the mountain pine beetle?" and "How many trees will I lose if the stand becomes infested with the beetle?" The first question is addressed in previously published management guidelines (Amman and others 1977; Cole and Cahill 1976). Answers to the second question depend on the rate of loss from an infestation. This paper describes a model that estimates the amount of tree and volume loss per year and the longevity of the infestation, and shows how the model can be incorporated into forest planning.

BACKGROUND

Most models for epidemic processes are based on continuous-infection assumption and treat epidemics in a fully probabilistic manner, and most of the processes considered are diseases. The continuous-infection concept assumes that an individual (the host tree) can be infectious from the moment it receives the infection (the beetle) until it dies, recovers, or is removed. This clearly is not the case with the mountain pine beetle. The mountain pine beetle has a discrete generation and discrete stages of growth, and its epidemic behavior does not fit the continuous-infection assumptions.

An alternative to the continuous-infection assumption was established by Reed and Frost in 1928 (Abbey 1952) and by Greenwood (1931). They postulated that the period of infectiousness is comparatively short, and the latent and incubation periods are constant (Bailey 1957). This alternative assumption appears to fit the epidemic behavior of the mountain pine beetle and amount of tree loss. In lodgepole pine stands in the Intermountain West, the period of infesting a tree (beetle attack) is fairly short (approximately 1 day for one tree and up to 4 to 6 weeks within a stand), the latent period is the time beetle development takes place without the emission of any infectious material (brood development), and the incubation period is the elapsed time between the receipt of the infection and the appearance of symptoms (time between attack and foliage discoloration). Both the latent and incubation periods can be considered constant in relation to the life cycle of the beetle and tree fade.

A first approximation model considers the latent and incubation periods as constant, the period of infectiousness as reduced to a single point, and a single attack as conferring immunity. At each stage in the epidemic, there are specific numbers of infectives and susceptibles. It is reasonable to assume that the susceptibles will yield a fresh crop of cases distributed in a binomial series at the next stage. This then creates a chain of binomial distributions; the actual probability of a new infection at any state depends on the numbers of infectives and susceptibles at the previous stage.

If we begin with one infested tree within a stand, or possibly several simultaneously infested trees, the infestation will spread in a series of stages, as each new generation of adult beetles attacks living green trees. If the stand of trees is suitable for successful infestation, we expect the number of trees killed at any stage to have a binomial distribution based upon numbers of susceptible and infested trees. Therefore, throughout the course of a mountain pine beetle epidemic, we have a chain of binomial distributions. The probability of a tree becoming infested at any generation depends upon the numbers of infested trees and susceptible green trees during the preceding generation of beetles.

Therefore, an epidemic started in a lodgepole pine stand by a single infested tree, or by several trees becoming infested simultaneously, will continue in a series of stages (generations of beetles) until either no more beetles are left to attack green, large diameter trees or no more green trees are left to be attacked. In each stage of the epidemic (each generation of beetles), there will be a specific number of infested trees and a specific number of susceptibles. The susceptibles can be attacked by a new generation of beetles, and the newly infested trees will be distributed in a binomial series. Thus, the chain of binomial distributions begins.

The assumptions underlying models based on discrete time usually consider all susceptible and infested individuals to be mixed together homogeneously. This situation is most nearly represented by small groups of trees but does not hold for large stands. However, incubation and latent periods are not variable, and the infesting of a tree can be considered as a relatively short period of time. As this model was refined, habitat type and volume yield factors were included. These factors govern tree and stand susceptibility and affect the life processes of beetle populations.

One important problem with the chain binomial model is that substantial departures from the assumptions of constant incubation and latent periods and a very short infectious period would invalidate the model. Another problem is failure to properly identify the links of the chain. However, if a highly variable incubation period occurs, or the symptoms cannot be identified correctly, there is still an alternative—to base our analysis on the total number of cases occurring during the course of the epidemic. Some precision is lost when the parameters are estimated. However, if the number infested is large, frequencies based on this number can be calculated directly and will probably be more accurate than those derived from the probabilities of the individual chains.

THE RATE OF LOSS MODEL

If p is the probability of a tree becoming infested in a given time interval, then $q = 1 - p$ is the probability of a tree not becoming infested. The probability of a tree becoming infested depends on the susceptibility or resistance of the tree, the infestivity of the beetle, the length of attack period, and the size of the attacking beetle population, as well as the environmental conditions of the stand.

If D_t is the number of trees infested at time t, then q^{D_t} is the probability that a specified tree will not be infested, and $1 - q^{D_t}$ is the probability that the tree will be infested. If there are G_t green trees capable of being infested in the population at time t, the expected number of infested trees produced at the time $t + 1$ is G_t times the probability of at least one tree being infested. Or:

$$D_{t+1} = G_t (1 - q^{D_t}) \text{ and } G_{t+1} = G_t q^{D_t}.$$

This equation provides a method of stepwise calculation of trees infested at successive time periods as shown in table 1.

If $G_t = 0$, all the trees are dead—no more susceptible trees are left—and the epidemic subsides due to food depletion. If $D_t = 0$, there are no more trees successfully producing beetles—and the epidemic subsides.

The Greenwood model postulates that the probability of a susceptible tree being infested is a constant and is not related to the number of infested trees. In other words, a susceptible tree in a stand with one infested tree is as likely to be attacked as the same tree surrounded by many infested trees. This is obviously not the case. Thus, we adopted the Reed-Frost model for susceptibility because it accounts for the increase in infestation pressure due to the number of infested trees. In the Reed-Frost model, the probability of a tree not being infested from only one source is taken to be a constant, q. The probability of not being infested from two sources is thus (q) (q), and consequently from n sources it is q^n.

The value of q, the probability of a tree not being infested from one source, can be calculated by solving the equation of G_{t+1} for q. This yields:

$$q = (G_{t+1}/G_t)^{(1/D_t)}$$

Theoretically, q will be a constant, but the real world is never constant. Thus the q for time t (q_t) varies slightly with t, and may be determined for each time interval. However, we found a closer prediction of D_{t+1} was obtained if several values for q_t were calculated, and q was estimated by q_t for several stands. We also found that precision of prediction increased with decreasing size of diameter classes. Estimates of tree mortality over time approximated true losses more closely when predicted by 2-inch (5.1-cm) diameter classes than by larger diameter classes.

Table 1.—*Calculation of a theoretical epidemic from the Reed-Frost model (p = 0.5)*

Time period	Number of dead trees	Number of susceptible trees	Calculation of D_{t+1} and G_{t+1}
0	1	100	$D_1 = 100 (1 - 0.95) = 5.00 = 5$ $G_1 = 100 - 5 = 95$
1	5	95	$D_2 = 95 (1 - 0.95^5) = 21.49 = 21$ $G_2 = 95 - 21 = 74$
2	21	74	$D_3 = 74 (1 - 0.95^{21}) = 48.80 = 29$ $G_3 = 74 - 49 = 25$
3	49	25	$D_4 = 25 (1 - 0.95^{49}) = 22.97 = 23$ $G_4 = 25 - 23 = 2$
4	23	2	$D_5 = 2 (1 - 0.95^{23}) = 1.39 = 1$ $G_5 = 2 - 1 = 1$
5	1	1	$D_6 = 1 (1 - 0.95^1) = 0.05 = 0$ $G_6 = 1 - 0 = 1$
6	0	1	

For high q values, peak mortality tended to be overestimated. By the third year, q usually becomes small due to the "high-grading" action of the beetle in thinning a stand, resulting in greater overestimation of tree mortality. However, the critical time during an infestation by the mountain pine beetle is at the point of change from endemic to epidemic. The value q applied to the larger diameter trees forecasts the pending infestation adequately in spite of the tendency toward overestimation.

The model assumes optimum conditions for the life of the epidemic. However, actual field conditions can cause beetle populations to deviate from predictions. Overestimation of tree mortality is not considered serious in most cases, particularly in the larger diameter classes. Epidemics usually begin in larger diameter trees preferred by the mountain pine beetle, and the rate of tree loss within these classes is critical. Thus, any factor that affects brood survival (such as thick phloem [food supply], which is correlated with larger diameters) will affect the rate of tree loss and, in turn, successive generations.

Dispersion of the beetle is also affected by stand characteristics such as species, age, stocking levels, growth rates, and diameter class distribution; and by site characteristics, including habitat type, soils, elevation, slope, and aspect. During the past decade the system of environmental classification by habitat type developed by Daubenmire for the Northern Rocky Mountain Forest Ecosystem has gained increasing acceptance in other areas of the West. This concept stresses use of the entire climax plant community as an environmental indicator that permits identification of environments (habitats) with similar biotic potentials. All environments (habitats) with the potential to support approximately the same mix of stable (climax) plant species are considered to be within the same habitat type regardless of successional status of the vegetation.

Recent data from the Forest Service Northern Region show that the extent of lodgepole pine mortality caused by the mountain pine beetle varies by habitat type group, and by habitat type within groups. This type of classification provides the framework essential for organizing information to select alternative management activities for habitat types.

MODEL TESTS AND REFINEMENT

Data from a mountain pine beetle infestation in the Bechler River Drainage of Yellowstone National Park (Klein and others 1978) were used to predict tree loss by 2-inch (5.1-cm) diameter classes (situation A, table 2; fig. 1). Trees were also grouped by 6- to 12-inch (15.2- to 30.5-cm), 14- to 16-inch (35.6- to 40.6-cm), greater than 16-inch (40.6-cm) diameters, and total stand (table 3; fig. 2 and 3).

Table 2.—*Predicted versus observed tree loss by year based on $\bar{q}_t$, the average probability of tree loss by 2-inch (5.1-cm) tree diameter class (Situation A, Klein and others 1978)*

Diameter class	Year of infestation	Number of trees per acre		$1/D_t$	q_t	Predicted tree loss
		Green	Dead			
6-inch (15.2-cm)	0	79.8	0.3	3.333	0.9875	0.14
	1	79.5	0	0	1.0000	0
	2	79.5	.3	3.333	.9857	.14
	3	79.2	2.1	.476	.9873	.99
	4	77.1	0	0	1.0000	0
	5	77.1	0	0	1.0000	0
	6	77.1	0	0		0
		Total loss:	2.7 (6.75/ha)	Average:	.9937	1.27 (3.175/ha)
8-inch (20.3-cm)	0	62.7	.8	1.250	0.984	0.90
	1	61.9	.8	1.250	.984	.89
	2	61.1	2.7	.370	.983	2.92
	3	58.4	8.1	.120	.982	7.99
	4	50.3	.7	1.430	.980	.63
	5	49.6	.5	2.000	.980	.63
	6	49.1	0	0		0
		Total loss:	13.6 (34.0/ha)	Average:	.982	13.96 (34.9/ha)
10-inch (25.4-cm)	0	38.8	0.8	1.250	0.974	1.09
	1	38.0	1.1	.909	.974	1.46
	2	36.9	3.9	.256	.972	4.79
	3	33.0	10.6	.0943	.964	10.38
	4	22.4	1.4	.714	.955	1.09
	5	21.0	.6	1.667	.953	.44
	6	20.4	.2	5.000		.14
	7	20.2	0	0		0
		Total loss:	18.6 (46.5/ha)	Average:	.965	19.39 (48.475/ha)
12-inch (30.5-cm)	0	17.0	0.6	1.667	0.942	0.95
	1	16.4	1.3	.769	.938	1.91
	2	15.1	2.8	.357	.932	3.54
	3	12.3	4.2	.238	.902	4.06
	4	8.1	1.2	.833	.875	.88
	5	6.9	.2	5.000	.863	.13
	6	6.7	.1	10.000		.64
	7	6.6	0	0		0
		Total loss:	10.4 (26.0/ha)	Average:	.909	11.87 (29.675/ha)

Table 2.—*con.*

Diameter class	Year of infestation	Number of trees per acre		$1/D_t$	q	Predicted tree loss
		Green	Dead			
14-inch (35.6-cm)	0	8.0	0.4	2.500	0.880	0.89
	1	7.6	1.2	833	.867	2.28
	2	6.4	2.2	.454	.826	3.07
	3	4.2	2.0	.500	.724	1.88
	4	2.2	.4	2.500	.606	.25
	5	1.8	2	5.000	.55	.10
	6	1.6	0	0		0
		Total loss:	6.4 (16.0/ha)	Average:	.743	8.47 (21.175/ha)
16-inch (40.6-cm)	0	2.1	0.3	3.333	0.598	0.624
	1	1.8	.1	3.333	5.45	.534
	2	1.5	.7	1.429	.407	.841
	3	.8	.3	3.333	.209	.238
	4	.6	.2	5.000	.078	.105
	5	.3	.1	10.000	.017	.033
	6	.2	0	0		0
		Total loss:	1.9 (4.75/ha)	Average:	309	2.375 (5.925/ha)
>16-inch (>40.6-cm)	0	2.6	0.3	3.333	0.582	0.63
	1	1.7	.4	2.500	511	.67
	2	1.3	.3	1.111	270	.08
	3	.4	.1	10.000	.056	.06
	4	.3	.3	5.000	.004	.06
	5	.1	0	0	0	0
	6	.1	0			0
		Total loss:	1.9 (4.75/ha)	Average:	285	2.29 (5.725/ha)
Total	0	211.0	5.0			5.2
	1	208.0	5.0			7.7
	2	203.0	14.0			16.2
	3	189.0	27.0			15.6
	4	162.0	4.0			3.0
	5	158.0	2.0			1.3
	6	156.0	1.0			.2
	7	155.0	0			0
		Total loss:	56.0 (140.0/ha)	Average:	.753	59.2 (148.0/ha)

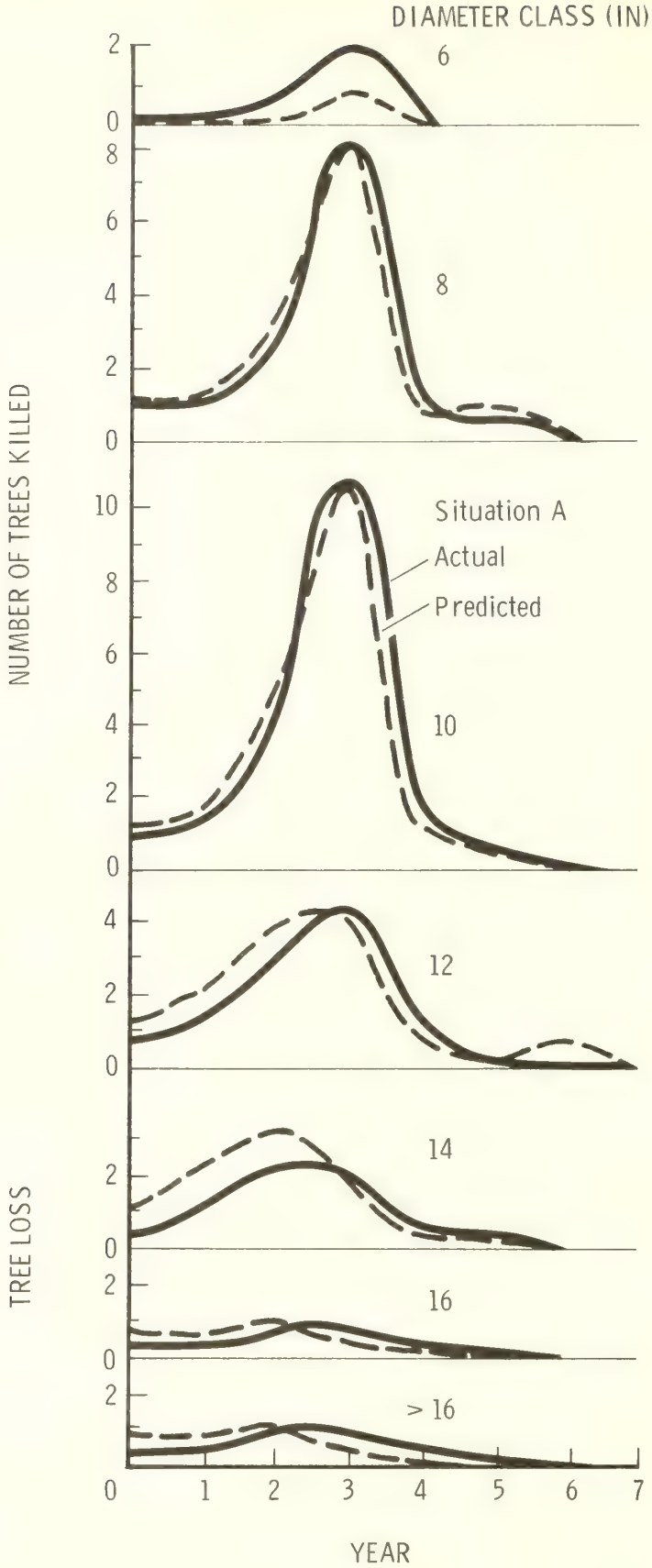


Figure 1.—Predicted versus observed tree loss by year based on q_t by 2-inch tree diameter class (Situation A, Klein and others 1978).

Table 3.—*Predicted versus observed tree loss by year based on $\bar{q}_t$, the average probability of tree loss, by tree diameter class and stand (Situation A, Klein and others 1978, grouped by greater diameter spread)*

Diameter class	Year of infestation	Number of trees per acre		$1/D_t$	q_t	Predicted tree loss
		Green	Dead			
6-12 inch	0	198.3	2.5	0.4000	0.997	2.5
(15.2-30.5-cm)	1	196.8	3.2	.3125	.995	3.1
	2	193.6	9.7	.103	.995	9.2
	3	183.9	25.0	040	.994	21.7
	4	158.9	3.3	.303	.994	2.6
	5	155.6	1.3	.769	994	1.2
	6	154.3	3	3.333	0	2
	7	154.0	0	0		
		Total loss:	44.3 (110.75/ha)		Average: 995	40.3 (100.75/ha)
14-16 inch	0	12.1	1.0	1.000	0.917	2.5
(35.6-40.6-cm)	1	11.1	1.9	.526	906	3.9
	2	9.2	3.8	263	869	5.4
	3	5.4	2.4	416	783	2.3
	4	3.0	8	1.250	679	5
	5	2.2	3	3.333	613	.15
	6	1.9	0	0	0	0
		Total loss:	10.2 (25.5/ha)		Average: .794	14.8 (37.0/ha)
>16-inch	0	4.1	0.6	1.667	0.768	1.6
(>40.6-cm)	1	[illegible]	7	1.429	727	[illegible]
	2	2.8	1.6	.625	.589	[illegible]
	3	1.2	4	2.500	363	3
	4	8	4	2.500	.177	2
	5	4	4	10.000	056	.03
	6	.3	0	0	0	0
		Total loss:	3.8 (9.5/ha)		Average: 447	5.9 (14.75/ha)

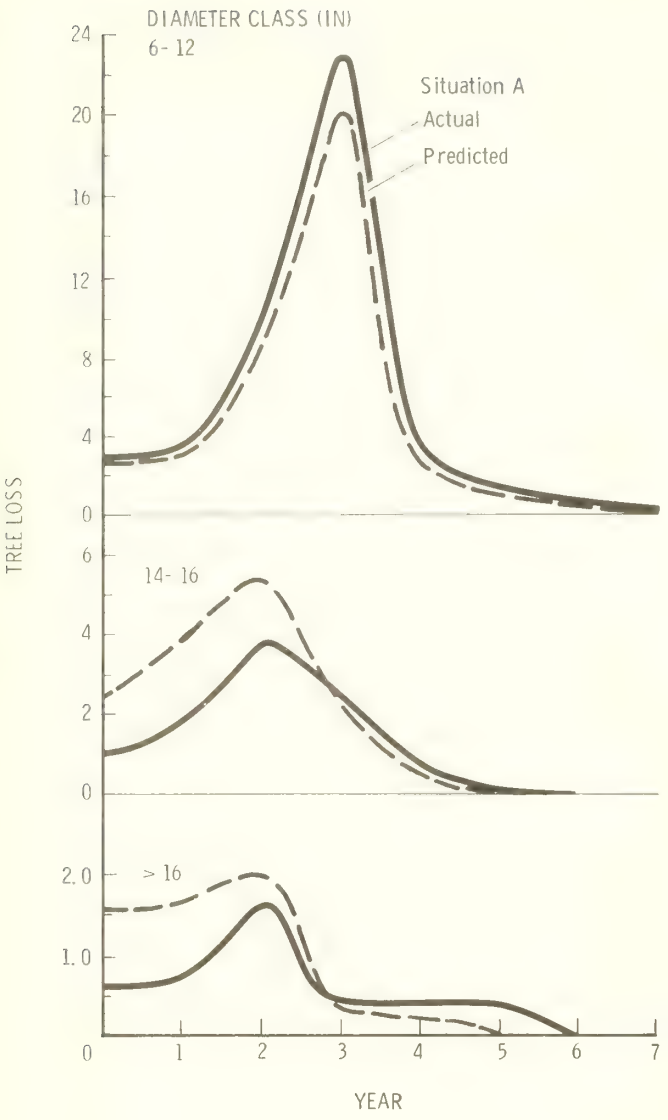


Figure 2.—Predicted versus ob-served tree loss by year based on q_t, by grouped tree diameter classes and total stand (Situation A, Klein and others 1978).

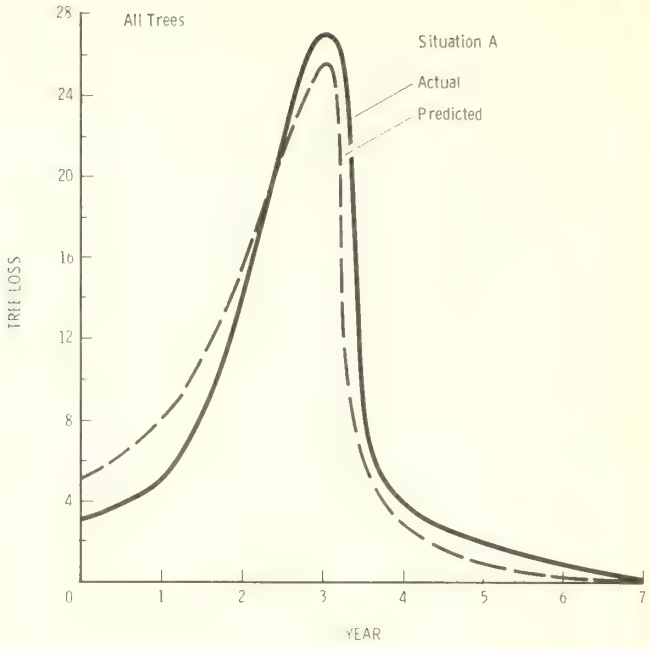


Figure 3.—Predicted versus observed tree loss by year for total stand based on q_t (Situation A, Klein and others 1978).

The second data set came from a mountain pine beetle infestation in the Gallatin River Drainage, and was used only for total tree loss, because the data were not originally taken by diameter classes (situation B). Tree loss over time did not fall into the usual bell-shaped pattern, yet the predicted tree loss approximated the actual double-peaked curve (table 4; fig. 4) (Burnell 1977).

Answers to the questions, "Which of the lodgepole pine stands are the most susceptible to mountain pine beetle outbreak development?" and "How many trees will the manager lose if the stand becomes infested?" depend upon risk. A definition of risk has two parts: (1) probability of an outbreak within a set time period, and (2) expected loss in the advent of an outbreak (Safranyik 1982). Reliable methods are not available to predict when an outbreak will develop, but we can predict the most susceptible stands and also forecast stand depletion in terms of stand structure should an epidemic occur. To date, six risk-rating systems have been developed that are based on climatic and tree/stand variables having a major effect on beetle survival and distribution. Rate of spread could be considered using historical maps (fig. 5) or mathematical models based on habitat type.

Table 4.—*Predicted versus observed tree loss by year based on $\overline{q}_i$, the average probability of tree loss by tree diameter class and stand (Situation B, Burnell 1977, grouped by total stand)*

Year of infestation	Number of trees per acre		$1/D_i$	q_i	Predicted tree loss
	Green	Dead			
0	370.2	3.6	0.278	0.997	6.6
1	366.6	8	1 250	.997	1.5
2	365.8	19.5	.0513	.997	34.1
3	346.3	16.4	.0609	.997	27.3
4	329.9	77.8	.0128	.999	106.5
5	252.1	31.8	.0315	.992	37.1
6	220.3	10.3	0971	987	11.1
7	210.0	0	0	0	0
	Total loss	160.2 (400.5/ha)	Average	995	224.2 (560.5/ha)

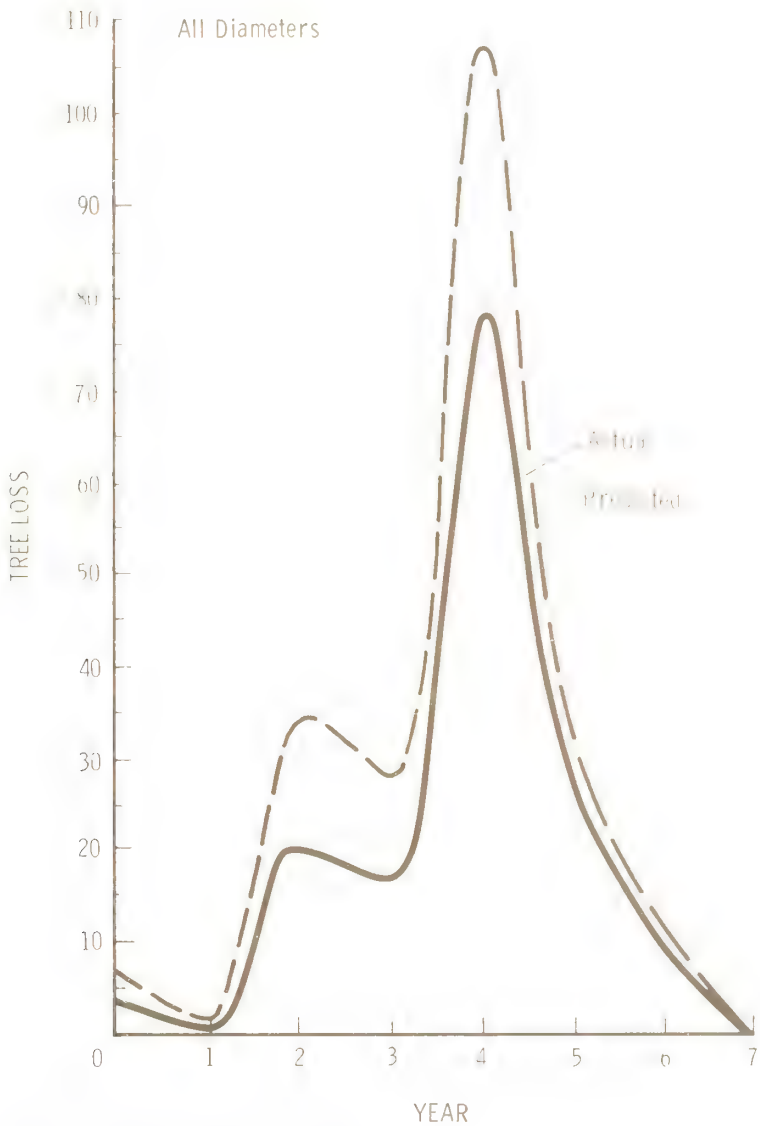
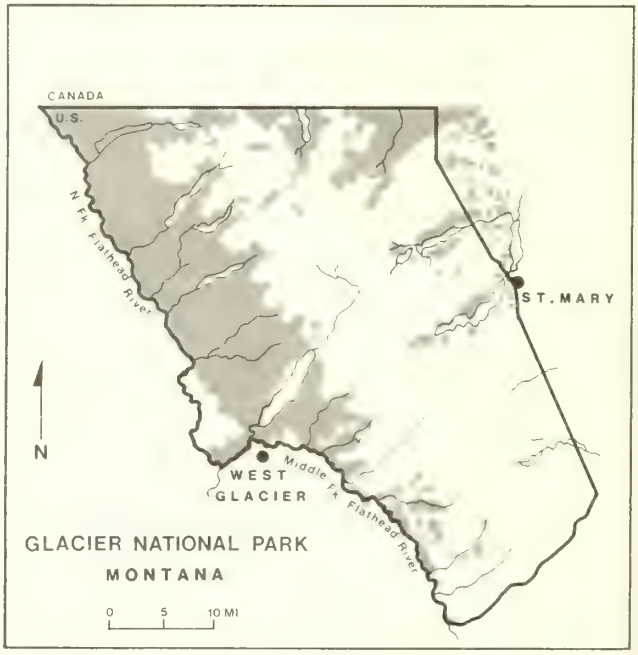


Figure 4.—Predicted versus observed tree loss by year based on q_i, by tree diameter class, grouped and total stand (Situation B, Burnell 1977).

1972

1975

1978



1980

Figure 5.—Chronology of mountain pine beetle infestations, Glacier National Park and Blackfeet Indian Reservation, Mont. 1972-1980. (McGregor and others 1982)

Historical maps are useful in areas that have suffered repeated severe outbreaks where remaining stands can be hazard rated. Through forest inventory and survey data, forest cover types can be delineated showing mature, overmature, pole, and reproduction-size stands. When location and stand composition are known, maps can be composed depicting susceptible stands. These maps provide a rough hazard rating over large areas, which managers can use to initiate strategies to prevent future infestations or to salvage logs and reduce fuel loads in stands devastated by the mountain pine beetle. Usually managers can expect that another epidemic will begin within 20 to 40 years, when remaining trees reach size classes with phloem thickness conducive to a population buildup (Amman 1975). However, this depends on characteristics of stands and how soon residual trees become susceptible; and it is likely that infestation recurrence will be prolonged in managed stands. Historical maps, timber type maps, and timber inventory surveys can provide the basis for hazard rating stands. The ratings can be in very broad, but also extremely accurate, categories (McGregor 1982). However, significant differences occur within areas rated high hazard as to the amount and rate at which mortality develops, peaks, and subsides in various stands. Relating mortality with habitat type on a stand basis has helped refine hazard rating of lodgepole pine stands in the Forest Service Northern Region.

The Insect and Disease Damage Survey Model (INDIDS) (Bousfield 1981) and our Rate of Loss Model were tested using approximately 1,200 stands with mountain pine beetle infestations ranging from 1 year to the end of the epidemic (McGregor and others 1982.) The INDIDS Model is used to analyze forest insect and disease data collected from variable or fixed plots. It uses summaries of detailed mensurational data of infested and residual green stands—a tree species, size class, and damage class for each designated survey type. Use of INDIDS Model results in computations of tree and volume loss and basal area killed per acre (Dilworth and Bell 1968).

The Rate of Loss Model was integrated with the INDIDS Model to estimate mortality trends for infested stands or to obtain loss estimates (tree, cubic, and board foot volume) by diameter class over infestation time for green stands, should they become infested (table 6).

Table 5.—*Estimated trees/acre and volume loss by diameter class over time using the rate of spread for mountain pine beetle model for lodgepole pine*
a. Mixed species stand: 25.4 percent alpine fir, 12.4 percent Engelmann spruce, 12.4 percent whitebark pine, 37.3 percent lodgepole pine, 12.4 percent Douglas-fir

FLATHEAD NATIONAL FOREST 710 07781 710

MOUNTAIN PINE BEETLE MODEL FOR LODGEPOLE PINE

LODGEPOLE PINE TREES PER ACRE AND CUBIC FEET VOLUME BEFORE AN OUTBREAK

	0-2.9	3-4.9	5-6.9	7-8.9	9-10.9	11-12.9	13-14.9	15-16.9	17-18.9	19+	Total
T/A	.00	.00	.00	.00	.00	31.85	31.37	.00	9.32	.00	72.54
Mort.	.00	.00	.00	.00	.00	1.12	1.57	.00	1.40	.00	4.09
CFA	.00	.00	.00	.00	.00	691.56	943.91	.00	457.15	.00	2,092.62

TREES PER ACRE LOSS DURING 10-YEAR OUTBREAK

	0-2.9		3-4.9		5-6.9		7-8.9		9-10.9		11-12.9		13-14.9		15-16.9		17-18.9		19+	
Year	GT	Mort	GT	Mort	GT	Mort	GT	Mort	GT	Mort	GT	Mort	GT	Mort	GT	Mort	GT	Mort	GT	Mort
1	.0	.00	.0	.00	.0	.00	.0	.00	.0	.00	27.6	3.12	18.7	11.10	.0	.00	1.4	6.55	.0	.00
2	.0	.00	.0	.00	.0	.00	.0	.00	.0	.00	20.5	7.12	.7	18.01	.0	.00	.0	1.37	.0	.00
3	.0	.00	.0	.00	.0	.00	.0	.00	.0	.00	10.4	10.09	.0	.69	.0	.00	.0	.00	.0	.00
4	.0	.00	.0	.00	.0	.00	.0	.00	.0	.00	4.0	6.42	.0	.00	.0	.00	.0	.00	.0	.00
5	.0	.00	.0	.00	.0	.00	.0	.00	.0	.00	2.1	1.82	.0	.00	.0	.00	.0	.00	.0	.00
6	.0	.00	.0	.00	.0	.00	.0	.00	.0	.00	1.8	.34	.0	.00	.0	.00	.0	.00	.0	.00
7	.0	.00	.0	.00	.0	.00	.0	.00	.0	.00	1.7	.06	.0	.00	.0	.00	.0	.00	.0	.00
8	.0	.00	.0	.00	.0	.00	.0	.00	.0	.00	1.7	.01	.0	.00	.0	.00	.0	.00	.0	.00
9	.0	.00	.0	.00	.0	.00	.0	.00	.0	.00	1.7	.00	.0	.00	.0	.00	.0	.00	.0	.00
10	.0	.00	.0	.00	.0	.00	.0	.00	.0	.00	1.7	.00	.0	.00	.0	.00	.0	.00	.0	.00

LODGEPOLE PINE TREES PER ACRE AND CFV AFTER AN OUTBREAK

	0-2.9	3-4.9	5-6.9	7-8.9	9-10.9	11-12.9	13-14.9	15-16.9	17-18.9	19+	Total	% Mortality
T/A	.00	.00	.00	.00	.00	1.74	.00	.00	.00	.00	1.74	97.6
CFA	.00	.00	.00	.00	.00	37.72	.08	.00	.00	.00	37.80	98.2

Attack	Unsec	LP Total	Percent
.00	.00	56.54	.00

Attack CFA	Unsec CFA	LPCFV Total	Percent CFV
.00	.00	1,608.99	.00

Table 5.— *con.*

b. Mixed species stand: 15 percent lodgepole pine; 85 percent Douglas-fir, subalpine fir, Engelmann spruce

FLATHEAD NATIONAL FOREST 734 07791 734

MOUNTAIN PINE BEETLE MODEL FOR LODGEPOLE PINE

LODGEPOLE PINE TREES PER ACRE AND CUBIC FEET VOLUME BEFORE AN OUTBREAK

	0-2.9	3-4.9	5-6.9	7-8.9	9-10.9	11-12.9	13-14.9	15-16.9	17-18.9	19+	Total
T/A	.00	.00	.00	.00	6.91	.00	11.48	.00	.00	.00	18.39
Mort	.00	.00	.00	.00	.14	.00	.58	.00	.00	.00	.72
CFA	.00	.00	.00	.00	143.42	.00	323.26	.00	.00	.00	466.68

TREES PER ACRE LOST DURING 10-YEAR OUTBREAK

	0-2.9		3-4.9		5-6.9		7-8.9		9-10.9		11-12.9		13-14.9		15-16.9		17-18.9		19+	
Year	GT	Mort	GT	Mort	GT	Mort	GT	Mort	GT	Mort	GT	Mort	GT	Mort	GT	Mort	GT	Mort	GT	Mort
1	.0	.00	.0	.00	.0	.00	.0	.00	6.7	.03	.0	.00	9.2	1.16	.0	.00	.0	.00	.0	.00
2	.0	.00	.0	.00	.0	.00	.0	.00	6.1	.01	.0	.00	7.1	2.03	.0	.00	.0	.00	.0	.00
3	.0	.00	.0	.00	.0	.00	.0	.00	6.1	.00	.0	.00	1.9	1.06	.0	.00	.0	.00	.0	.00
4	.0	.00	.0	.00	.0	.00	.0	.00	6.1	.00	.0	.00	.9	1.25	.0	.00	.0	.00	.0	.00
5	.0	.00	.0	.00	.0	.00	.0	.00	6.1	.00	.0	.00	.4	.14	.0	.00	.0	.00	.0	.00
6	.0	.00	.0	.00	.0	.00	.0	.00	6.1	.00	.0	.00	.4	.06	.0	.00	.0	.00	.0	.00
7	.0	.00	.0	.00	.0	.00	.0	.00	6.1	.00	.0	.00	.4	.00	.0	.00	.0	.00	.0	.00
8	.0	.00	.0	.00	.0	.00	.0	.00	6.1	.00	.0	.00	.4	.00	.0	.00	.0	.00	.0	.00
9	.0	.00	.0	.00	.0	.00	.0	.00	6.1	.00	.0	.00	.4	.00	.0	.00	.0	.00	.0	.00
10	.0	.00	.0	.00	.0	.00	.0	.00	6.1	.00	.0	.00	.4	.00	.0	.00	.0	.00	.0	.00

LODGEPOLE PINE TREES PER ACRE AND CFV AFTER AN OUTBREAK

	0-2.9	3-4.9	5-6.9	7-8.9	9-10.9	11-12.9	13-14.9	15-16.9	17-18.9	19+	Total	% Mortality
T/A	.00	.00	.00	.00	6.78	.00	.41	.00	.00	.00	7.18	61.0
CFA	.00	.00	.00	.00	130.53	.00	11.51	.00	.00	.00	141.04	69.8

Attack	Unsec	LP Total	Percent
.00	.00	10.45	.00

Attack CFA	Unsec CFA	LPCFV Total	Percent CFV
.00	.00	242.77	.00

Table 5.— *con.*

c. Mixed species stand: 65 percent alpine fir, 29 percent Engelmann spruce, and 6 percent lodgepole pine

GALLATIN NATIONAL FOREST 611 05049 611

MOUNTAIN PINE BEETLE MODEL FOR LODGEPOLE PINE

LODGEPOLE PINE TREES PER ACRE AND CUBIC FEET VOLUME BEFORE AN OUTBREAK

	0-2.9	3-4.9	5-6.9	7-8.9	9-10.9	11-12.9	13-14.9	15-16.9	17-18.9	19+	Total
T/A	.00	60.00	33.67	176.07	30.58	49.86	14.09	12.30	.00	4.11	380.68
Mort	.00	.00	.13	2.25	.63	1.76	.70	1.76	.00	.62	7.85
CFA	.00	.00	149.92	1,452.10	417.93	1,271.31	455.69	495.95	.00	247.44	4,490.34

TREES PER ACRE LOSS DURING 10-YEAR OUTBREAK

	0-2.9		3-4.9		5-6.9		7-8.9		9-10.9		11-12.9		13-14.9		15-16.9		17-18.9		19+	
Year	GT	Mort	GT	Mort	GT	Mort	GT	Mort	GT	Mort	GT	Mort	GT	Mort	GT	Mort	GT	Mort	GT	Mort
1	.0	.00	60.0	.00	33.5	.03	166.8	6.97	29.3	.66	40.7	7.44	10.9	2.53	1.3	9.20	.0	.00	1.6	1.88
2	.0	.00	60.0	.00	33.5	.01	147.0	19.85	28.6	.69	20.0	20.66	5.1	5.73	.0	1.34	.0	.00	.2	1.46
3	.0	.00	60.0	.00	33.5	.00	102.5	44.49	27.9	.69	2.8	17.22	.9	4.19	.0	.00	.0	.00	.0	.13
4	.0	.00	60.0	.00	33.5	.00	45.7	56.82	27.2	.68	.5	2.25	.3	.66	.0	.00	.0	.00	.0	.00
5	.0	.00	60.0	.00	33.5	.00	16.3	29.41	26.6	.65	.4	.10	.2	.05	.0	.00	.0	.00	.0	.00
6	.0	.00	60.0	.00	33.5	.00	9.5	6.74	26.0	.61	.4	.00	.2	.00	.0	.00	.0	.00	.0	.00
7	.0	.00	60.0	.00	33.5	.00	8.4	1.10	25.4	.56	.4	.00	.2	.00	.0	.00	.0	.00	.0	.00
8	.0	.00	60.0	.00	33.5	.00	8.3	.17	24.9	.50	.4	.00	.2	.00	.0	.00	.0	.00	.0	.00
9	.0	.00	60.0	.00	33.5	.00	8.2	.03	24.5	.44	.4	.00	.2	.00	.0	.00	.0	.00	.0	.00
10	.0	.00	60.0	.00	33.5	.00	8.2	.00	24.1	.38	.4	.00	.2	.00	.0	.00	.0	.00	.0	.00

LODGEPOLE PINE TREES PER ACRE AND CFV AFTER AN OUTBREAK

	0-2.9	3-4.9	5-6.9	7-8.9	9-10.9	11-12.9	13-14.9	15-16.9	17-18.9	19+	Total	% Mortality
T/A	.00	60.00	33.51	8.25	24.10	.43	.22	.00	.00	.02	126.52	66.8
CFA	.00	.00	149.19	68.01	329.32	10.98	7.02	.00	.00	1.25	565.76	87.4

Attack	Unsec	LP Total	Percent
.00	.00	190.20	.00

Attack CFA	Unsec CFA	LPCFV Total	Percent CFV
.00	.00	2,256.65	.00

Table 5.— *con.*

d. Mixed species stand: 10 percent alpine fir, 77.1 percent lodgepole pine, 12.6 percent Douglas-fir

GALLATIN NF 709 02014 709

MOUNTAIN PINE BEETLE MODEL FOR LODGEPOLE PINE

LODGEPOLE PINE TREES PER ACRE AND CUBIC FT. VOLUME BEFORE AN OUTBREAK

	0-2.9	3-4.9	5-6.9	7-8.9	9-10.9	11-12.9	13-14.9	15-16.9	17-18.9	19+	TOTAL
T/A	94.74	.00	72.32	99.93	68.68	34.83	14.23	5.28	1.14	1.65	370.82
MORT.	.00	.00	11.47	18.72	11.95	14.45	5.89	.47	1.14	1.61	65.77
CFA	.00	.00	393.49	925.85	779.59	761.69	461.41	167.38	75.42	141.69	3,706.61

TREES PER ACRE DEAD DURING 10-YEAR OUTBREAK

	0-2.9		3-4.9		5-6.9		7-8.9		9-10.9		11-12.9		13-14.9		15-16.9		17-18.9		19+	
Year	GT	Mort.	GT	Mort.	GT	Mort.	GT	Mort.	GT	Mort.	GT	Mort.	GT	Mort.	GT	Mort.	GT	Mort.	GT	Mort.
1	94.7	.00	.0	.00	56.1	4.89	97.8	23.12	54.0	14.73	1.1	1....	1..	0.91	1.0	1.14	.0	.00	.0	.00
2	94.7	.00	.0	.00	54.9	1.39	97.5	20.02	10.1	9.75	1.1	1.47	.	1.47	..	1.22	.0	.00	.0	.00
3	94.7	.00	.0	.00	54.3	.67	96.3	13.52	14.1	6.79	.8	.5..	.1	.00	.1	.31	.0	.00	.0	.00
4	94.7	.00	.0	.00	54.1	.20	21.1	6.00	9.1	1.11	.6	.01	.1	.00	.1	.03	.0	.00	.0	.00
5	94.7	.00	.0	.00	54.0	.07	19.1	1.80	9.1	.11	.6	.00	.1	.00	.1	.00	.0	.00	.0	.00
6	94.7	.00	.0	.00	54.0	.03	18.8	.66	9.0	.01	.5	.00	.1	.00	.1	.00	.0	.00	.0	.00
7	94.7	.00	.0	.00	54.0	.01	18.6	.22	8.9	.01	.5	.00	.1	.00	.1	.00	.0	.00	.0	.00
8	94.7	.00	.0	.00	54.0	.00	18.5	.07	8.9	.01	.5	.00	.1	.00	.1	.00	.0	.00	.0	.00
9	94.7	.00	.0	.00	54.0	.00	18....	....	....	....	....	.00	.1	.00	.1	.00	.0	.00	.0	.00
10	94.7	.00	.0	.00	54.0	.00	18....	....	....	....	....	.00	.1	.00	.1	.00	.0	.00	.0	.00

[illegible]

	0-2.9	3-4.9	5-6.9	7-8.9	[illegible]	[illegible]	[illegible]	[illegible]	17-18.9	19+	TOTAL	[illegible]
T/A	94.74	.00	50.00	19....	8.0	.00	.11	.00	.00	.00	172.14	...
CFA	.00	.00	272.11	111.58	48.88	14.81	2.11	.70	.00	.00	450.19	...

ATTACK	PNSEC	LP TOTAL	PERCENT
65.31	.00	161.67	40.39

ATTACK CFA	PNSEC CFA	LPCFV TOT.	PERCENT CFV
1118.04	.00	1709.80	65.39

Table 5.— *con.*

e. Mixed species stand: 28.6 percent alpine fir, 0.2 percent whitebark pine, 60.6 percent lodgepole pine, 10.6 percent Douglas-fir

GALLATIN NF 709 02012 709

MOUNTAIN PINE BEETLE MODEL FOR LODGEPOLE PINE

LODGEPOLE PINE TREES PER ACRE AND CUBIC FT. VOLUME BEFORE AN OUTBREAK

	0-2.9	3-4.9	5-6.9	7-8.9	9-10.9	11-12.9	13-14.9	15-16.9	17-18.9	19+	TOTAL
T/A	245.45	.00	16.28	8.81	59.05	24.13	3.95	.00	.00	.00	357.66
MORT.	.00	.00	.06	8.81	26.13	9.93	.20	.00	.00	.00	45.13
CFA	.00	.00	57.19	78.37	840.12	501.31	94.03	.00	.00	.00	1,571.02

TREES PER ACRES LOSS DURING 10-YEAR OUTBREAK

	0-2.9		3-4.9		5-6.9		7-8.9		9-10.9		11-12.9		13-14.9		15-16.9		17-18.9		19+	
Year	GT	Mort.	GT	Mort.	GT	Mort.	GT	Mort.	GT	Mort.	GT	Mort.	GT	Mort.	GT	Mort.	GT	Mort.	GT	Mort.
1	245.5	.00	.0	.00	16.2	.01	.0	.00	13.0	19.94	5.5	8.69	3.5	.21	.0	.00	.0	.00	.0	.00
2	245.5	.00	.0	.00	16.2	.00	.0	.00	6.4	6.60	2.4	3.10	3.3	.22	.0	.00	.0	.00	.0	.00
3	245.5	.00	.0	.00	16.2	.00	.0	.00	5.0	1.34	1.8	.62	3.1	.21	.0	.00	.0	.00	.0	.00
4	245.5	.00	.0	.00	16.2	.00	.0	.00	4.8	.23	1.7	.10	2.9	.19	.0	.00	.0	.00	.0	.00
5	245.5	.00	.0	.00	16.2	.00	.0	.00	4.8	.04	1.7	.02	2.8	.16	.0	.00	.0	.00	.0	.00
6	245.5	.00	.0	.00	16.2	.00	.0	.00	4.8	.01	1.7	.00	2.6	.13	.0	.00	.0	.00	.0	.00
7	245.5	.00	.0	.00	16.2	.00	.0	.00	4.8	.00	1.7	.00	2.5	.10	.0	.00	.0	.00	.0	.00
8	245.5	.00	.0	.00	16.2	.00	.0	.00	4.8	.00	1.7	.00	2.5	.07	.0	.00	.0	.00	.0	.00
9	245.5	.00	.0	.00	16.2	.00	.0	.00	4.8	.00	1.7	.00	2.4	.05	.0	.00	.0	.00	.0	.00
10	245.5	.00	.0	.00	16.2	.00	.0	.00	4.8	.00	1.7	.00	2.4	.04	.0	.00	.0	.00	.0	.00

LODGEPOLE PINE TREES PER ACRES AND CFV AFTER AN OUTBREAK

	0-2.9	3-4.9	5-6.9	7-8.9	9-10.9	11-12.9	13-14.9	15-16.9	17-18.9	19+	TOTAL	% MORTALITY
T/A	245.5	.00	16.21	.00	4.76	1.67	2.38	.00	.00	.00	270.47	24.6
CFA	.00	.00	56.94	.00	67.68	34.60	56.78	.00	.00	.00	216.01	86.3

ATTACK	UNSEC	LP TOTAL	PERCENT
44.87	.00	278.91	16.09

ATTACK CFA	UNSEC CFA	LPCFV TOT.	PERCENT CFV
710.12	.00	1,247.91	56.90

Table 5.— *con.*

f. Pure lodgepole pine stand

FLATHEAD NF 747 05973 747

MOUNTAIN PINE BEETLE MODEL FOR LODGEPOLE PINE

LODGEPOLE PINE TREES PER ACRE AND CUBIC FT. VOLUME BEFORE AN OUTBREAK

	0-2.9	3-4.9	5-6.9	7-8.9	9-10.9	11-12.9	13-14.9	15-16.9	17-18.9	19+	TOTAL
TPA	85.71	300.00	141.46	48.93	21.69	4.00	2.00	1.43	.00	.00	605.27
MORT.	.00	.00	.74	.43	.47	.00	.00	1.19	.00	.00	.82
CFA	.00	.00	48.47	59.74	301.62	.00	.00	181.53	.00	.00	1,306.87

TREES PER ACRE LOST DURING 10-YEAR OUTBREAK

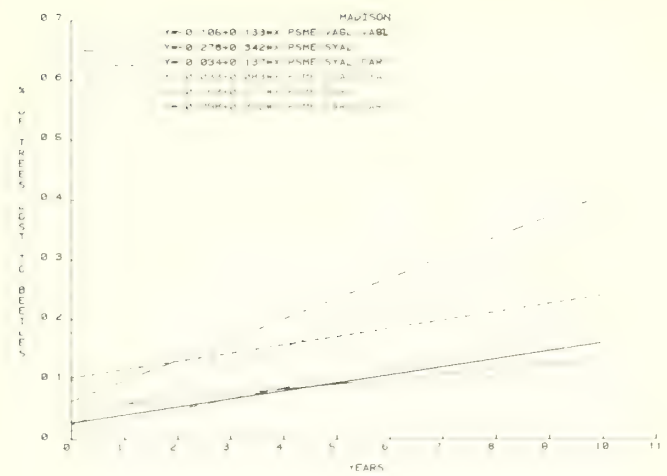
	0-2.9		3-4.9		5-6.9		7-8.9		9-10.9		11-12.9		13-14.9		15-16.9		17-18.9		19+	
Year	CF	Mort.	CF	Mort.	CF	Mort.	CF	Mort.	CF	Mort.	CF	Mort.	CF	Mort.	CF	Mort.	CF	Mort.	CF	Mort.
1	85.7	.00	300.00	.00	140.46	.00	48.93	.00	21.69	.00	4.00	.00	2.00	.00	1.43	.00	.00	.00	.00	.00
2	85.7	.00	300.00	.00	140.46	.00	48.93	.00	21.69	.00	4.00	.00	2.00	.00	1.43	.00	.00	.00	.00	.00
3	85.7	.00	300.00	.00	140.46	.00	48.93	.00	21.69	.00	4.00	.00	2.00	.00	1.43	.00	.00	.00	.00	.00
4	85.7	.00	300.00	.00	140.46	.00	48.93	.00	21.69	.00	4.00	.00	2.00	.00	1.43	.00	.00	.00	.00	.00
5	85.7	.00	300.00	.00	140.46	.00	48.93	.00	21.69	.00	4.00	.00	2.00	.00	1.43	.00	.00	.00	.00	.00
6	85.7	.00	300.00	.00	140.46	.00	48.93	.00	21.69	.00	4.00	.00	2.00	.00	1.43	.00	.00	.00	.00	.00
7	85.7	.00	300.00	.00	140.46	.00	48.93	.00	21.69	.00	4.00	.00	2.00	.00	1.43	.00	.00	.00	.00	.00
8	85.7	.00	300.00	.00	140.46	.00	48.93	.00	21.69	.00	4.00	.00	2.00	.00	1.43	.00	.00	.00	.00	.00
9	85.7	.00	300.00	.00	140.46	.00	48.93	.00	21.69	.00	4.00	.00	2.00	.00	1.43	.00	.00	.00	.00	.00
10	85.7	.00	300.00	.00	140.46	.00	48.93	.00	21.69	.00	4.00	.00	2.00	.00	1.43	.00	.00	.00	.00	.00

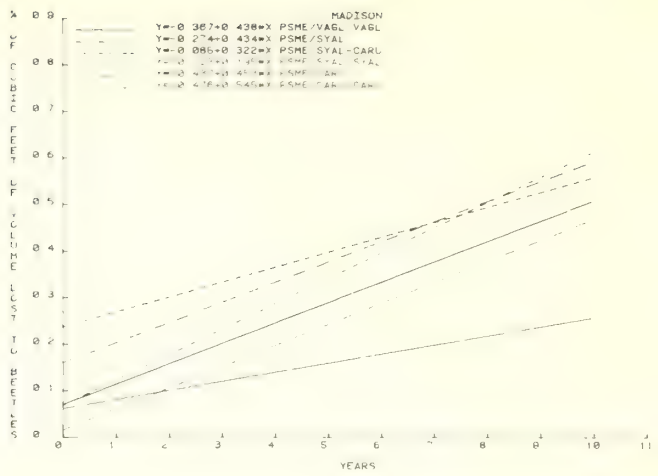
CONDITION AFTER [illegible] YEAR OUTBREAK

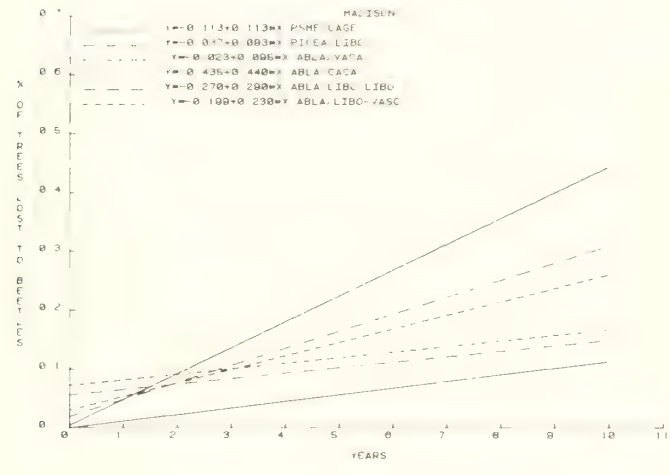
	0-2.9	3-4.9	5-6.9	7-8.9	9-10.9	11-12.9	13-14.9	15-16.9	17-18.9	19+	TOTAL	% MORTALITY
TPA	85.71	300.00	141.46	48.93	21.69	4.00	2.00	1.43	.00	.00	605.27	.0
CFA	.00	.00	48.47	59.74	301.62	.00	.00	181.53	.00	.00	1,306.87	0.0

AVERAGE DIAMETER	TOTAL BASAL AREA	TOTAL PERCENT MORTALITY
.00	49.00	.00

AVERAGE CFA	MERCH CFA	TOTAL CFA	PINE SAW	FC
.00	.00	1,306.11		.01




MADISON
Y=-0 387+0 438*X PSME/VAGL VAGL
Y=-0 274+0 434*X PSME/SYAL
Y=-0 086+0 322*X PSME SYAL-CARU
% OF CUBIC FEET OF VOLUME LOST TO BEETLES
YEARS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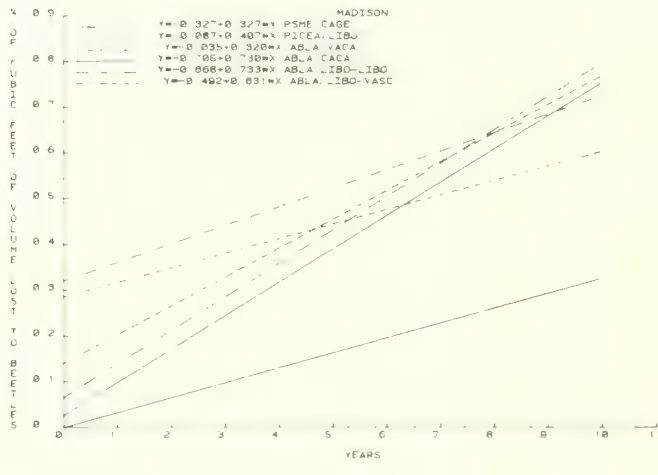
Y=-0 023+0 086*X ABLA VACA
Y=-0 435+0 440*X ABLA CACA
Y=-0 270+0 280*X ABLA LIBO LIBO
Y=-0 100+0 230*X ABLA LIBO-VASC
% OF TREES LOST TO BEETLES
YEARS


MADISON
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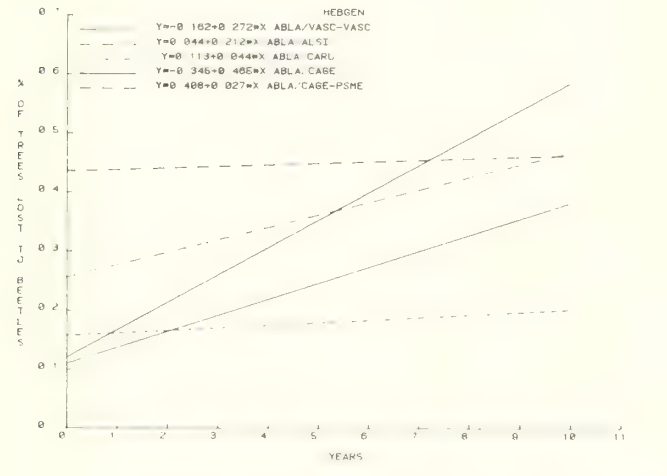
Y=-0 087+0 407*X PICEA LIBO
Y=-0 035+0 320*X ABLA VACA
Y=-0 705+0 730*X ABLA CACA
Y=-0 868+0 733*X ABLA LIBO-LIBO
Y=-0 402+0 831*X ABLA LIBO-VASC
% OF CUBIC FEET OF VOLUME LOST TO BEETLES
YEARS



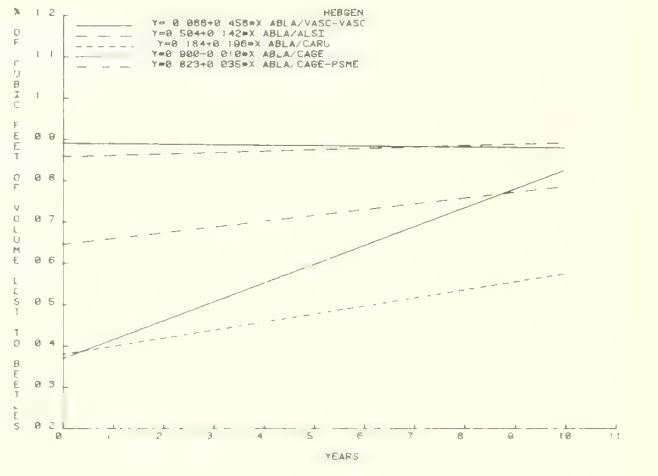

HEBGEN
Y= 0 088+0 458*X ABLA/VASC-VASC
Y=0 504+0 142*X ABLA/ALSI
Y=0 184+0 106*X ABLA/CARU
Y=0 900-0 010*X ABLA/CAGE
Y=0 823+0 035*X ABLA/CAGE-PSME
% OF CUBIC FEET OF VOLUME LOST TO BEETLES
YEARS

Figure 6.—Predicted lodgepole pine trees and volume loss from mountain pine beetle by habitat type over time for Madison Ranger District, Beaverhead National Forest, and Hebgen Lake Ranger District, Gallatin National Forest, Mont.

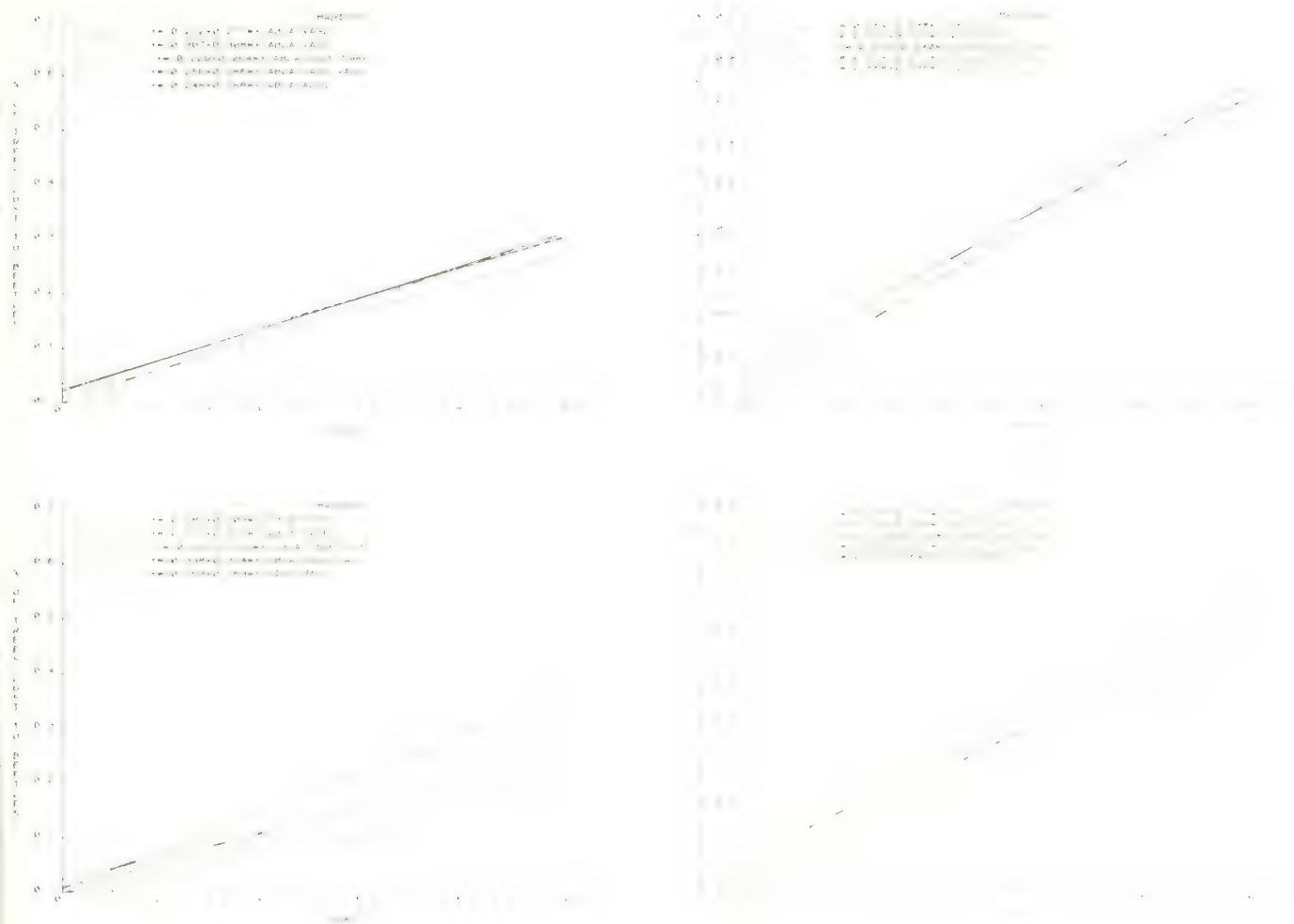


Figure 6.—(con.)

Stand data were then subjected to analysis of variance and analysis of covariance for completely randomized design and graphed to show lodgepole pine mortality by habitat type over time (fig. 6). Analysis shows that the percentage of lodgepole pine killed and volume loss vary by habitat type.

In some habitat types, tree mortality increased rapidly and most susceptible trees and all volume are killed in a relatively short time (fig. 6; ABLA/VASC-VASC, ABLA/ALSI). In others, mortality may occur over a 10-year period and never exceed 30 percent of the stand (fig. 6, ABLA/CARU, ABLA/LIBO-LIBO). All susceptible trees may be killed in other habitat types, but it may require 8 to 10 years. These data provide guidance as to which stands within those classed as high hazard should receive priority management. For example, management may be postponed until the next decade if stand mortality does not exceed 20 to 30 percent over a 10-year period. Meanwhile, stands can be rated and management implemented in the stands containing habitat types where considerable tree mortality or volume loss is predicted to occur over a short time. By putting the higher risk stands under management, loss would probably be prevented in some high-, many moderate-, and many low-risk stands.

INTEGRATION WITH FORPLAN

The Forest Service currently uses FORPLAN, a linear programing model (Johnson and others 1980), for land management planning which is the basis for land use allocations and scheduling of management activities. The management activities and associated products, costs, and environmental effects used in FORPLAN are reflected in prescriptions for stands within analysis areas. In the Forest Service Northern Region, analysis areas are lands that meet certain common classification criteria; these lands are not usually contiguous. Classification criteria include habitat type, timber size class, slope class, and other characteristics. Prescriptions describe specific management practices used to manage specific stands.

One approach to modeling tree mortality caused by the mountain pine beetle using FORPLAN has been to predict susceptible areas within analysis areas and probable mortality over two decades. Although it might be possible to predict rate of loss caused by the beetles throughout a forest, this information would be of little value for adjusting yield tables if the locations of high-, moderate-, and low-risk stands are not identified within analysis areas. The FORPLAN model would spread bark

beetle effects over the next two decades for all stands within analysis areas, which would not allow scheduling earlier harvest of stands with a high probability of infestation and mortality.

Another approach is recommended when the location of stands within analysis areas is identified through timber surveys or stand examinations. Beetle attack may then be simulated by a "prescription" that shows the effects of an epidemic in the absence of timber management. If other management practices were not implemented, it would be necessary to constrain the beetle "prescription" by assignment to a certain acreage. Thus there would be two prescriptions—one for some stands in parts of the analysis area with infestation, and one for other parts with no effects of infestation.

Stands in the Helena National Forest were analyzed in a FORPLAN run by grouping habitat types so mortality factors could be directly applied to yield tables. A procedure was adopted and used to adjust yield tables based on the coefficients developed for the Helena National Forest plan (Brohman and others 1982). Coefficients were based on the assumption that a 50 percent loss of lodgepole pine would occur over a 5-year period. The estimated loss as a percentage of volume by age classes was determined as shown:

$$Y_1' = Y_1 (1 - {}^1\!/_4\ L)$$
$$Y_1' = Y_2 (1 - {}^3\!/_4\ L)$$
$$Y_j' = Y_j (1 - L),\ j \geq 3$$

where

L = proportion of volume lost to beetles (50 percent = 0.50),
Y_j = tabular volume for decade j of the plan, and
Y_j' = adjusted volume expected to exist in decade j.

Such coefficients must be derived for each habitat type or habitat type group to be applicable to the model. Decade 1, 2, or 3 of the Forest Plan may correspond to different decades in the yield table for different stands or habitat type groups within analysis areas. For example, if groups of stands are 105 years old, then Y_1 is the tabular yield shown at 110 years (25 percent loss by year 5). If the current age is 165 years, then Y_1 is the tabular yield shown for 170 years (25 percent loss by year 5, and 75 percent loss by year 10 at 175 years). The graphs in figure 7 were developed using this approach and the INDIDS/Rate of Loss Model for the Helena National Forest in the absence of beetle attack. The factor or proportionality is (1−L), the proportion of stand volume not killed.

That the predicted results graphed in figure 7 will actually happen is questionable. Beetle-induced mortality will reduce competition for trees that are not attacked. However, trees not susceptible to bark beetle attack are usually smaller and less vigorous. These trees will probably respond to a decrease in competition. But amount of response will depend on tree age and various site factors. We do not know at what rate the remaining live stand will grow compared to what it would have done without attack.

The final step in the FORPLAN run for the Helena National Forest plan was to adjust existing yield tables by the appropriate coefficient for each habitat type group. Regenerated stand tables were not adjusted, because management should prevent mountain pine beetle outbreaks over a rotation. The assumption that the beetle will infest susceptible stands throughout the National Forest in the next 20 years may not be totally correct, but it seems probable based on available information. By including coefficients in the yield tables, the FORPLAN model should show which highly susceptible lodgepole stands need immediate harvesting, and which stands should be harvested before becoming highly susceptible. By using assessments from FORPLAN and harvesting in high-hazard, susceptible stands before an epidemic develops, land managers should be able to minimize tree mortality caused by the beetle.

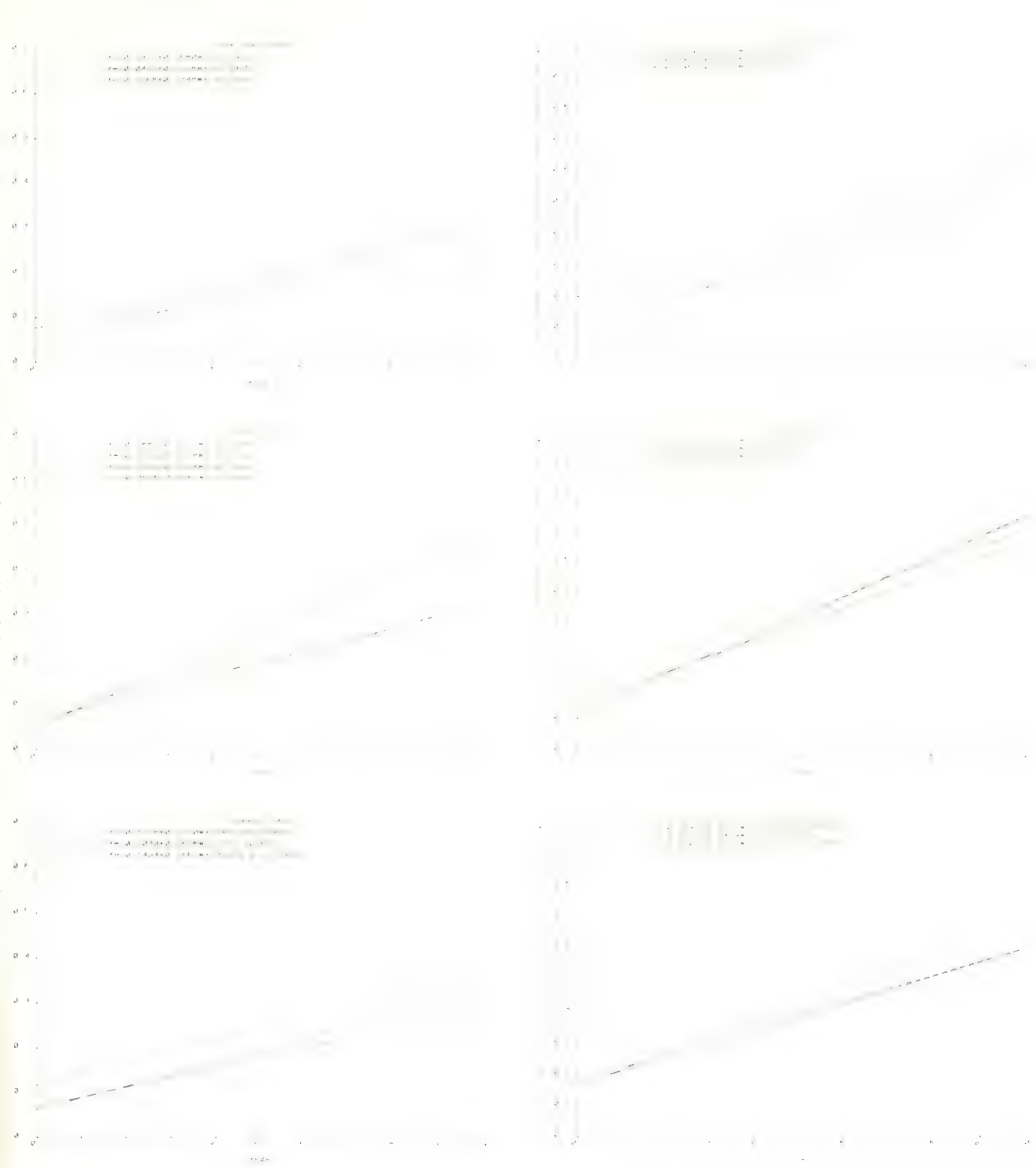


Figure 7.—Projected tree and volume loss from mountain pine beetle for lodgepole pine habitat type groups within dry fir, cool slopes, and mesic sites on the Helena National Forest.

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Forest managers have less than a 50 percent chance of growing lodgepole pine to 16-inch diameters in unmanaged stands because of recurrent depredation from the mountain pine beetle. Hazard rating methods provide techniques for managers to identify susceptible stands. The Rate of Loss Model refines existing risk rating systems, and provides a method for predicting tree and volume loss by habitat types. This model is provided to assist land managers in projecting tree mortality over time, and as a link with the FORPLAN Model for use in forest planning.

KEYWORDS: Mountain pine beetle, *Dendroctonus ponderosae* Hopkins, risk rating model, lodgepole pine, *Pinus contorta* var. *latifolia*, forest planning

Department of

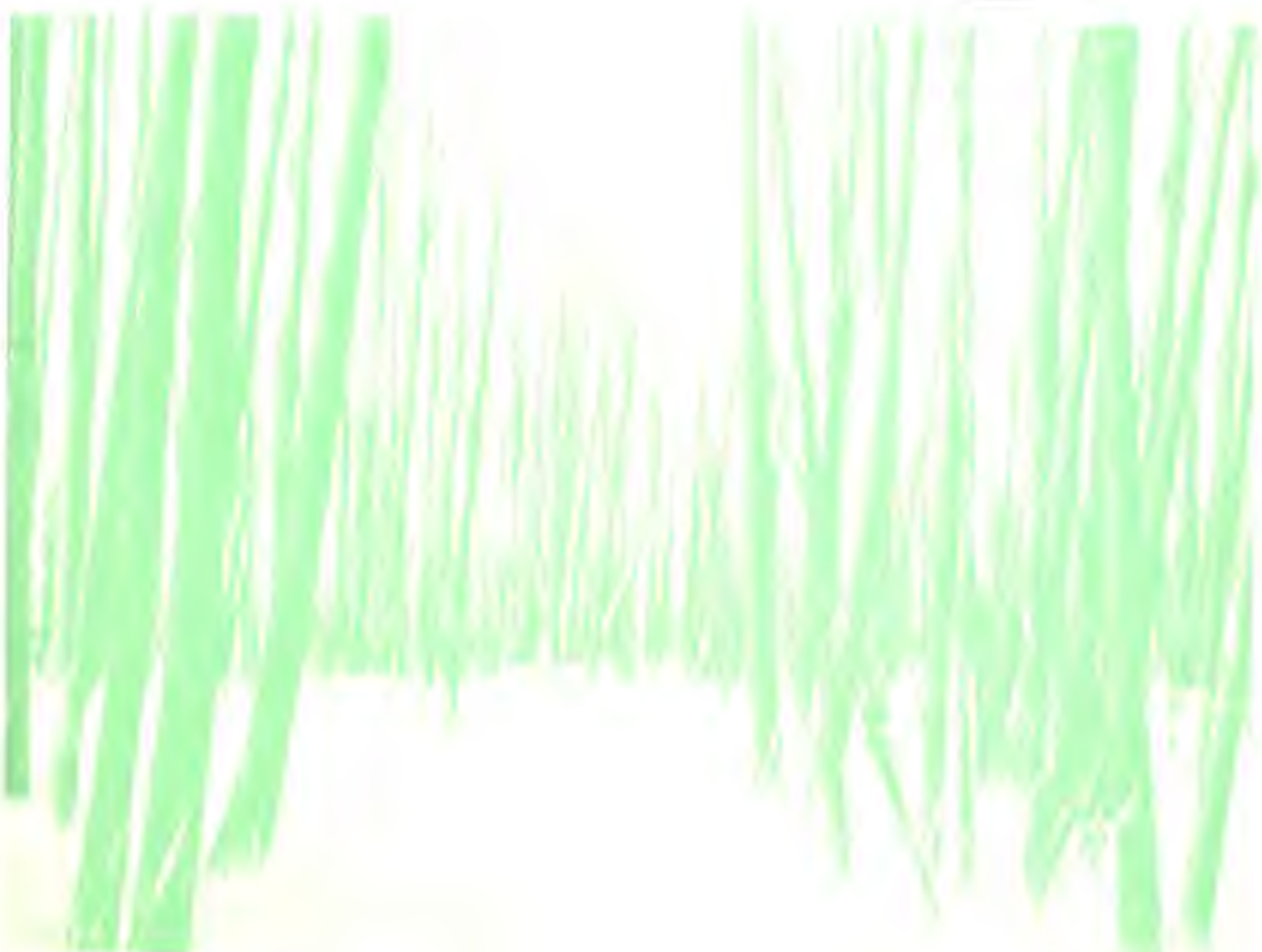
Intermountain
Forest and Range
Experiment Station

INT-113

Early Postfire Revegetation in a Western Montana Douglas-fir Forest

M. T. Dyrness
James R. Hansen
William C. Krueger

DEPARTMENT



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RESEARCH SUMMARY

A severe stand-destroying wildfire burned a 1,200-acre (486 ha) second-growth Douglas-fir forest (primarily Douglas-fir/ninebark habitat type) near Missoula, Mont., in July 1977. Most of the burned area was aerially seeded with exotic grasses during November 1977 while covered with snow.

Seeded orchardgrass and the native pinegrass are the most competitive species after 5 years. Orchardgrass is dominant in most areas. Shrubs have achieved dominance in most ravines and on some upland sites. On many upland sites, however, secondary colonization by shrubs will be necessary for a well-defined shrub stage to become established. The recovery of understory plants has been much more rapid in the ravines than on any upland sites. Tree regeneration is presently scarce, suggesting that reforestation will be slow.

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Early Postfire Revegetation in a Western Montana Douglas-fir Forest

M. F. Crane
James R. Habeck
William C. Fischer

INTRODUCTION

The wildfire that burned part of Pattee Canyon (fig. 1) on July 16 and 17, 1977, was a fast-spreading, intense crown fire. It burned 1,200 acres (486 ha) of land consisting mainly of Douglas-fir forest in the *Pseudotsuga menziesii/Physocarpus malvaceus* h.t. (PSME/PHMA; Douglas-fir/ninebark) as described by Pfister and others (1977). The Pattee Canyon burn presented an opportunity to study vegetative recovery following a severe wildfire in the extensive, interior Douglas-fir forest of western Montana. Such studies began in spring 1978.

THE STUDY AREA

Location

The Pattee Canyon drainage is located in the north end of the Sapphire Mountains in west-central Montana just southeast of Missoula. Pattee Creek drains the area and is fed by more than a dozen first- to third-order tributaries draining the side ridges. During spring runoff these small first- and second-order streams may flow overland their entire length, but in summer they become intermittent.

The fire burned a portion of the north-facing slope of the canyon lying below Mount Dean Stone (fig. 1). Land holdings in the area are divided among private, State, and Federal ownerships (fig. 1).

Geology and Soils

Bedrock in Pattee Canyon consists of quartzites and argillites of the Belt Series. Pattee Canyon was not glaciated during the Pleistocene ice ages. Glacial Lake Missoula, however, extended into Pattee Canyon (Alden 1953).

Soils in the study area are Tevis series with Mitten-Tevis complex on some upper slopes (L. T. Stem, USDA Soil Conservation Service, personal communication, 1980). These gravely loam inceptisols are colluvial soils derived from argillite and quartzite. The presence of an andic layer differentiates soils of the Mitten-Tevis complex from those of the Tevis series.

Climate

Climate in the Missoula area is strongly influenced by the Pacific Ocean where most of the area's weather originates. By the time the Pacific air masses reach Missoula, however, much of the moisture has been released. According to the National Weather Service, Missoula receives an average of 12 to 15 inches (305 to 381 mm) precipitation annually. Most of the moisture in Missoula and Pattee Canyon falls as snow during the winter or as rain showers during May and June. Midsummers are usually dry.

Pattee Canyon receives more moisture than Missoula itself. National Weather Service data from the Missoula Airport station and from a climatological station located on the north side of Pattee Canyon at about 3,740 feet (1 140 m) elevation are summarized in table 1. This comparison indicates that precipitation amounts in Pattee Canyon are generally higher than those recorded at the Missoula Airport station. Based on these data, Pattee Canyon gets an average of 85 percent greater precipitation than Missoula in spring and about 30 to 40 percent more during other seasons.

Vegetation

During a geographical study of Pattee Canyon (circa 1975) Bruce Bugbee (1981; personal communication) described habitat types in terms of Pfister and others (1972), preliminary forest habitat types of western Montana. The most widespread habitat type in the burned area was a *Pseudotsuga menziesii/Physocarpus malvaceus* h.t., *Physocarpus malvaceus* phase (PSME/PHMA-PHMA; Douglas-fir/ninebark, ninebark phase). *Pseudotsuga menziesii/Physocarpus malvaceus* h.t., *Calamagrostis rubescens* phase (PSME/PHMA-CARU; Douglas-fir/ninebark, pinegrass phase) occupied drier slopes and Douglas-fir scree occurred on the driest ridges. The upper slopes near the ridge were *Pseudotsuga menziesii/Vaccinium globulare* h.t., (PSME/VAGL; Douglas-fir/blue huckleberry) and, extending down the ravines, the coolest, moist areas were occupied by *Abies lasiocarpa/Linnaea borealis* h.t. (ABLA/LIBO; subalpine fir/twinflower).

Figure 1.—The Pattee Canyon fire area near Missoula, Mont., as shown by a 1972 aerial photograph.

Table 1.—Comparison of precipitation data from Missoula Airport Station and Pattee Canyon climatological station (source: National Weather Service Climatological Data)

Month	Precipitation amount					
	1976		1977		1978	
	Missoula Airport	Pattee Canyon	Missoula Airport	Pattee Canyon	Missoula Airport	Pattee Canyon
	Inches (millimeters)					
Jan.	0.90 (22.9)	1.03 (26.2)	0.66 (16.8)	0.80 (20.3)	1.15 (29.2)	1.46 (37.1)
Feb.	1.04 (26.4)	1.47 (37.3)	.18 (4.6)	.06 (1.5)	.66 (16.8)	1.49 (37.8)
Mar.	.40 (10.2)	.65 (16.5)	.98 (24.9)	1.50 (38.1)	.67 (17.0)	1.16 (29.5)
Apr.	.94 (23.9)	2.02 (51.3)	.08 (2.0)	.14 (3.6)	1.08 (27.4)	
May	.79 (20.1)	1.36 (34.5)	2.13 (54.1)	3.42 (86.9)	1.98 (50.3)	
June	1.52 (38.6)	3.19 (81.0)	.66 (16.8)	1.08 (27.4)	.77 (19.6)	
July	1.20 (30.5)	1.50 (38.1)	.72 (18.3)	.94 (23.9)	.57 (14.5)	
Aug.	.88 (22.4)	1.45 (36.8)	1.28 (32.5)	1.33 (33.8)	1.11 (28.2)	
Sept.	.58 (14.7)	.85 (21.6)	1.67 (42.4)	1.92 (48.8)	1.78 (45.2)	
Oct.	.33 (8.4)	.49 (12.4)	.72 (18.3)	1.01 (25.7)	.01 (.3)	
Nov.	.22 (5.6)	.63 (16.0)	1.02 (25.9)	1.58 (40.1)	1.00 (25.4)	
Dec.	.25 (6.4)	.33 (8.4)	2.88 (73.2)	4.16 (105.7)	.99 (25.1)	
Total	9.04 (229.9)	14.96 (380.2)	12.97 (329.7)	17.93 (455.7)	11.75 (298.7)	

Schuler's 1968 vegetation study in Pattee Canyon included some stands within and near the area subsequently burned in 1977. His original field data for these stands, as well as examination of pre-1977 aerial photographs and the fire-killed forest (fig. 2) indicate that much of the preburn forest was composed of dense, stagnating, pole-sized Douglas-fir (*Pseudotsuga menziesii*). Western larch (*Larix occidentalis*), ponderosa pine (*Pinus ponderosa*), and above 4,600 feet (1 402 m), lodgepole pine (*Pinus contorta*) were also present. The north slopes of Pattee Canyon have been roaded and subjected to selective logging thoughout the 1890-1960 period on both Federal and private lands (fig. 1).

The general vegetation pattern of Pattee Canyon demonstrates a trend toward increasingly more mesic species as one proceeds up the canyon. Slope exposure is an added influence, with more mesic species occurring on the north-facing slopes of the canyon.

A description of prefire vegetation was also obtained from observation of unburned stands adjacent to the burned area. One such stand (ravine stand 7) is in a relatively dry ravine with no established creek bed nor sign of annual overland flow. A dense overstory was composed of about 50 percent Douglas-fir, 40 percent

Figure 2.—Fire-killed stand of dense pole-sized trees in Pattee Canyon. This stand had been predominantly Douglas-fir.

western larch and 10 percent ponderosa pine. Tree ring counts indicated a stand age of about 70 to 80 years. The understory was layered. The tall shrub layer consisted of Rocky Mountain maple (*Acer glabrum*) and some serviceberry (*Amelanchier alnifolia*). Below these arborescent shrubs were lower shrubs including ninebark (*Physocarpus malvaceus*) and white spirea (*Spiraea betulifolia*), with a sparse herbaceous layer of heartleaf arnica (*Arnica cordifolia*), pinegrass (*Calamagrostis rubescens*), sidebells shinleaf (*Pyrola secunda*), western rattlesnake plantain (*Goodyera oblongifolia*), and western meadowrue (*Thalictrum occidentale*). There was also a well developed moss layer and a large amount of litter on the forest floor.

Fire Frequency

A fire history study for the north slope of Pattee Canyon, including the area burned in 1977, is in progress (Habeck, J. R.; unpublished data). Fire scars, mostly from ponderosa pine snags and stumps, provide the basis for the fire chronology. Nine samples, with five to nine fire scars each, have been analyzed using the methods described by Arno and Sneck (1977). Between approximately 1700 and 1900, the sampled area of Pattee Canyon experienced fires severe enough to scar the trees at an average interval of 15.8 years. Some fires scarred only one of the sample trees and thus may have been limited in extent or may have burned with such a low severity as not to scar other trees. It appears to have been more common for fires to cover large areas of the north slope or even the entire north slope because trees 2 or more miles apart exhibit similar fire dates based on a preliminary analysis of the data. During the century prior to settlement, 1780 to 1880, widespread fires occurred on an average of one per decade. The fire frequency in Pattee Canyon compares well with the mean fire-free interval of 13 years for the period 1600–1910 on similar sites in the neighboring Bitterroot Mountains (Arno 1980).

Prior to settlement, fires in western Montana resulted from summer lightning storms and Indian ignitions (Barrett 1981; Barrett and Arno 1982). Barrett's study and Arno's earlier (1976) study suggest that most of these fires were ground fires of low-to-moderate severity and frequent fires precluded heavy accumulations of fuel.

Based on fire scar analysis, tree aging, and an interpretation of the original Federal land survey records (Habeck, J. R.; unpublished data), the presettlement forest in Pattee Canyon appears to have been maintained by fire as an open, nearly parklike forest, with ponderosa pine on drier ridges, western larch in moist areas, and a scattering of mature Douglas-fir. Fire was effectively eliminated from Pattee Canyon throughout much of the 1900–77 period; selective logging removed the largest trees; and the open forests changed to densely stocked, closed-canopied stands easily capable of supporting high intensity crown fires.

The Fire

The Pattee Canyon fire started in dry grass near the west end of Pattee Canyon at about 4:20 in the afternoon July 16, 1977. Fire behavior was influenced by extreme fire weather: high temperature, low relative humidity, and strong, gusty winds. The Fire Danger Rating was, consequently, very high. The wind-driven fire spread quickly up the grassy slope and into adjacen conifers, where it crowned almost immediately. The fire then began its main run up Pattee Canyon toward the southeast with its smoke column pushed horizontal. The fire was extremely intense at this point and numerous spot fires started far ahead of the front (Jerry Williams, Montana State Division of Forestry, 1981; personal communication). Self-induced winds, along with the fire's direction up the hill, kept the fire away from the floor o the canyon and the many homes located there. As the fire burned across the north slope ravines, each ravine i turn acted as a chimney, funneling the fire up the ravine. Near the upper ridge the fire met gradient winds blowing the fire back upon itself. When the fire reached its eastern boundary, it met the developed spot fires. These spot fires then became backfires. The fire completed its main run by 5:15 p.m. (fig. 3). Fire suppressio efforts were then directed at putting out spot fires. The fire was declared contained the second day (July 17) and controlled the third day (July 18).

The fire burned about 1,200 acres (486 ha) and destroyed six homes (Fischer and Books 1977). It burne with greatest severity across sections 4 and 3 and the lower two-thirds of section 10 (fig. 3), with fire whirls in the western half of sections 3 and 10. In the southern (upper) portion of section 10 fire treatment was inconsistent, with vegetation in some sectors burned severely. I other areas the overstory was killed but the needles and small twigs on the trees were not consumed and the duf was not entirely removed from the soil. In section 11 th fire consisted of numerous spot fires, which collectively were much less uniform and less intense, leaving partially scorched crowns in some areas while confined to the ground elsewhere.

A postfire analysis of fire intensity in Pattee Canyon (Rothermel 1977) was divided into two parts: probable fire behavior in the grazed grass at the ignition point, and probable fire behavior in surface fuels under the timber (table 2). Crown fire intensity was not assessed but is estimated to have been at least tenfold that of th surface fire (Rothermel 1977).

Postfire Treatments

Immediately following the fire a team of Federal and State specialists inspected the burn and prescribed seeding with grass as a watershed rehabilitation measure. Aerial seeding was accomplished under the direction of USDA Soil Conservation Service during November while the area was snow covered. One private parcel on the west side of the fire was not seeded at the owner's request (fig. 1). The seed mixture was varied according to elevation (table 3).

During the winter of 1977-78, landowners in the lower portion of the burn conducted salvage logging to remove dead trees. Such logged areas were avoided for study purposes in order to prevent confusing fire effects with effects of tree removal and mechanical scarification. The "study area" then is limited to the burned area in sections 10 and 11 (fig. 3).

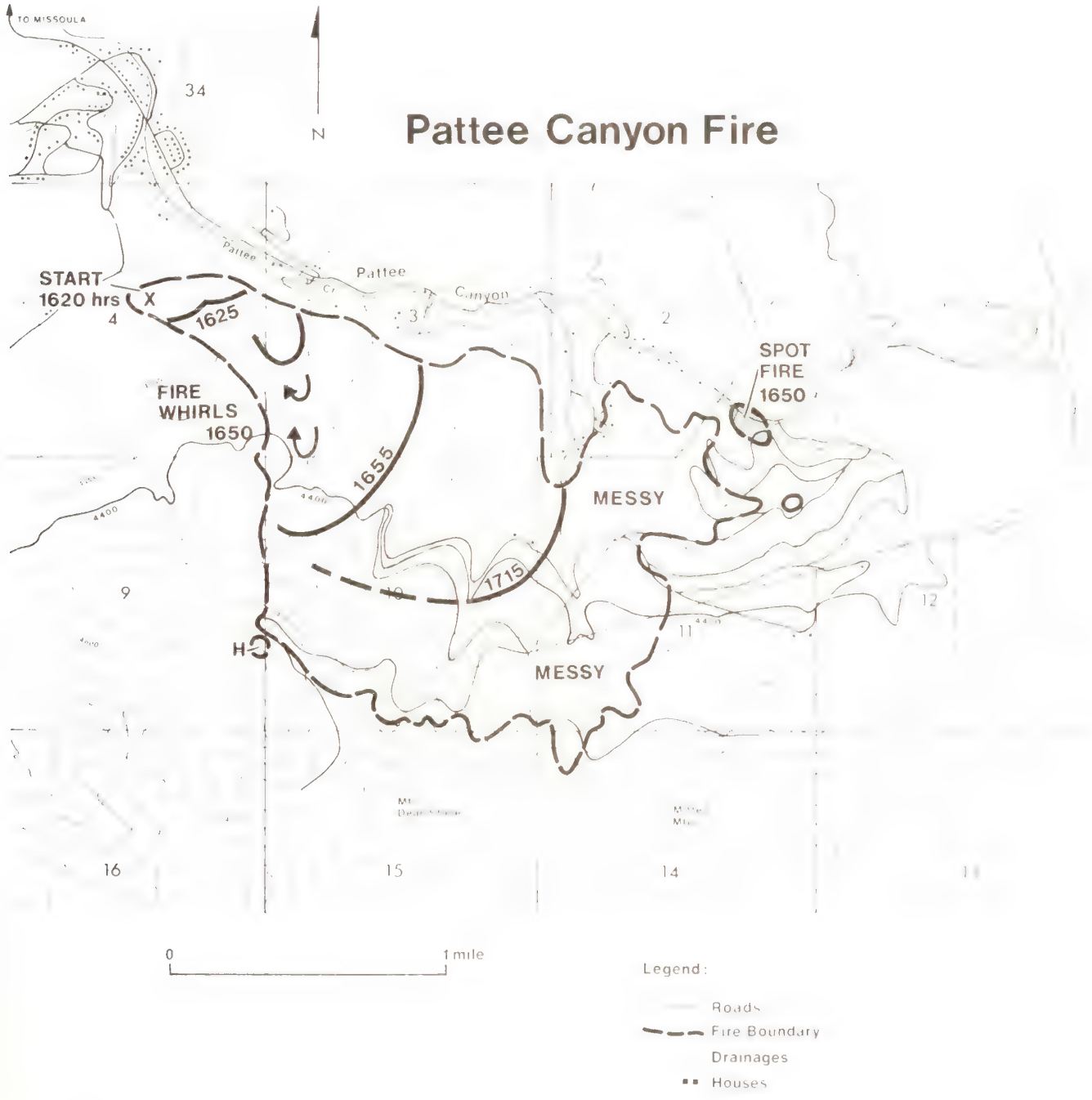

Figure 3.—Fire progress and area burned from start at about 4:20 p.m. to completion of its main run at 5:15 p.m., July 16, 1977.

Table 2.—Calculated fire behavior for Pattee Canyon Fire, July 16, 1977 (Rothermel 1977)

Fuel type	Calculated fire behavior		
	Rate of spread	Flame length	Fireline intensity
	Ft/min (m/min)	*Ft (m)*	*BTU/ft/sec (Cal/cm²/sec)*
Grazed grass	103 (31.4)	4.5 (1.4)	151 (41.0)
Forest floor	31 (9.5)	9.5 (2.9)	759 (205.9)

Table 3.—Commercial hybrid grasses seeded, and seeding rates, for Pattee Canyon burn; the 4,400-foot level is indicated on figure 3

Commercial grass species	Elevation	
	Below 4,400 ft (1 340 m)	Above 4,400 ft (1 340 m)
	Lb/acre(kg/ha)	
Latar orchard grass *(Dactylis glomerata)*	4.0 (4.5)	4.0 (4.5)
Luna pubescent wheatgrass *(Agropyron trichophorum* and *A. intermedium)*	19.0 (21.3)	
Kenmount tall fescue *(Festuca arundinaceae)*		8.0 (9.0)
Manchar smooth brome *(Bromus inermis)*		14.0 (15.7)

HE STUDIES

Since 1977, different research scientists have con-
ıcted four separate but related studies in the Pattee
anyon burn. The studies had two common objectives:
examine the vegetative recovery and to determine the
fect of seeded grass on that recovery.

Two parallel studies of the initial vegetative recovery
ere established in spring 1978, one in upland areas
nderson 1979) and one in ravines (Keller [Crane] 1980).
milar field methods were used for both studies, making
rect comparisons possible. Plots were permanently
arked, to facilitate long-term studies of vegetation
covery in the burn. These two initially separate studies
ere combined during the 1982 field season. Fuel
ading was also studied in both upland and ravine areas
ring 1978, 1979, and 1980 using plots in the same
ands as the vegetation studies.

A third study evaluated the response of ground
yophytes and lichens to the fire. The study was begun
summer 1978 using the same permanently marked
ot transects as the upland and ravine vegetation
udies. The fourth study, aimed at describing the
stribution of conifer regeneration, was conducted dur-
g the summer of 1980. This study used a systematic
ld design, with plots set equidistant along contour
es extending through the burn at specific elevations.

tudy Methods and Results

EGETATIVE RECOVERY ON UPLAND SITES

Field methods on upland sites. Preferential stand
lection was based on site homogeneity, as judged by
ysical environmental variables and remnants of prefire
getation. Thirteen stands were located on open slopes
d ridges. Table 4 lists physical variables for all stands.
ie upland stands are numbered 15 through 27. The
cations of upland and ravine stands in the burned area
e shown in figure 4. Initially upland stands were
mpled in early summer and again in late summer of
78 and 1979. In 1982 stands were sampled in late
mmer only. The late summer samples represent max-
um development of most species. Appendix A-1 lists
land site cover data.

Vegetation was sampled using the nested plot design
scribed by Stickney (1980). Vascular plant
menclature follows Hitchcock and Cronquist (1973).
ientific and common names for species mentioned
rein are listed in appendix D.

It was difficult to determine cover values for in-
idual grass species during the first year following the
e. All grass species were therefore recorded simply as
rass" if the combined grass cover was one-sixth plot
greater. In 1979 some data were recorded in a
rass" category, but data for principal species were
orded by species. During the 1982 remeasurement all
ass data were recorded by species. Those species with
s than one-sixth plot cover were recorded as
scellaneous vegetation if they collectively totaled one-
th cover rather than having a separate category for
asses (Stickney 1980).

Table 4.—*Sample stand physical data (see figure 4 for stand location within fire area)*

Stand	Elevation		Exposure	Slope
	Feet	*Meters*	*Degrees*	*Degrees*
1	3,970	1 210	312	9
2	4,060	1 240	355	9
3	3,940	1 200	10	10
4	4,030	1 230	35	9
5	4,170	1 270	55	11
6	4,280	1 305	50	15
7	4,430	1 350	360	20
8	4,720	1 440	60	32
9	4,910	1 500	55	33
10	4,790	1 460	55	33
11	4,430	1 350	15	15
12	4,560	1 390	20	15
13	4,690	1 430	360	30
14	4,230	1 290	25	11
15	4,100	1 250	330	8
16	4,400	1 340	330	9
17	4,100	1 250	345	17
18	4,300	1 310	345	18
19	4,300	1 310	350	31
20	4,700	1 430	277	34
21	4,800	1 460	325	26
22	5,100	1 550	350	26
23	5,050	1 540	317	22
24	5,100	1 550	307	33
25	5,600	1 710	333	19
26	5,250	1 600	360	38
27	5,100	1 550	338	27

Analysis of upland site data. The data from the permanent vegetative sample plots were analyzed by the USDA Forest Service's LOGBURN computer program (LOGBURN was created by L. Jack Lyon in 1966. It is on system at Intermountain Forest and Range Experiment Station, Missoula, Mont.). Cover values for each species from all plots were averaged for each stand and converted to a 0.01 ha standard. Because this standard equals 100 m^2, the values given for cover in the tables may be read directly as either meters squared per hundredth hectare or as percentage of ground covered. The volume of space occupied by each species was determined by multiplying the cover by the representative height. Volumes were averaged and converted to a meter cubed per hundredth hectare standard. Because the cover and volume data are converted to a standard based in part on the size of the plot in which the plants were measured, there may be rare cases in which cover and volume values appear to go down as the plant grows in height and is measured in the next larger plot. Tree data are summarized as basal area in decimeters squared per hundredth hectare.

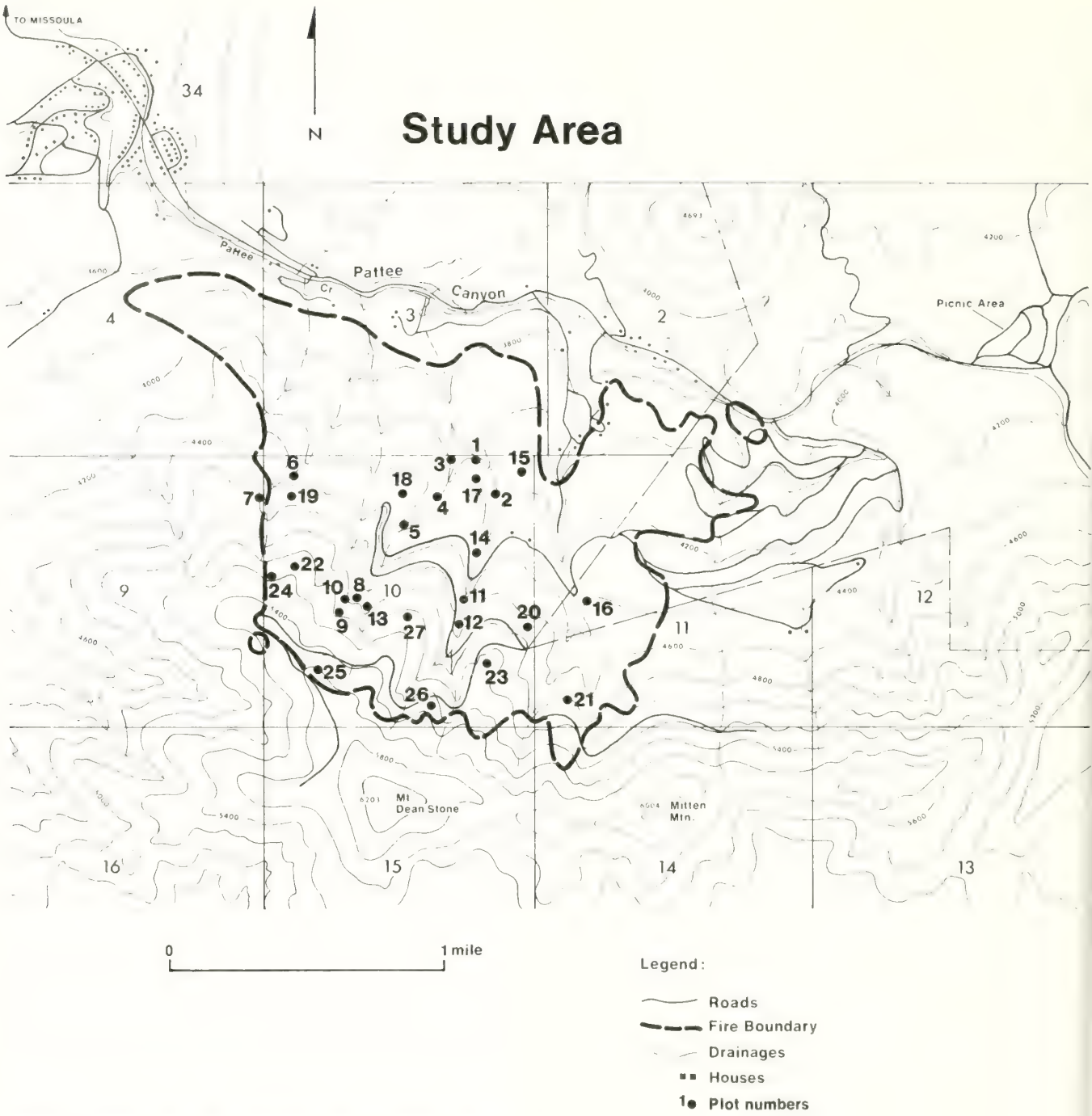

Figure 4.—Study area map. Numbers refer to stand plots.

Study results on upland sites. Table 5 shows the general pattern of recovery for upland seral community life-forms and the most important species within each life-form. Shrub cover and volume are low for the first 5 years since shrub resprouts are scattered on most upland sites. Stand 19 represents one of the exceptions to this trend. Shrub seedlings were noted in many stands during the summer of 1982. Herbaceous species, particularly grasses, dominate most sites.

Figure 5 shows the pattern of grass development, using the mean cover and volume for all upland stands. Pinegrass bloomed profusely during the summer of 1978 and somewhat less energetically in 1979. Subsequent seedling establishment observed in 1979 and 1980 coupled with vegetative spread account for the increase in pinegrass. The reasons for the decline of orchardgrass are unclear.

Table 5.—Upland cover and volume means for stands 16 through 27. Stand 15 was not included in these means because it was disturbed by grazing in 1982. Height data were not taken for grasses in 1978

	Cover			Volume		
	1978	1979	1982	1978	1979	1982
	Percent or m²/0.01 ha			*m³/0.01 ha*		
Shrubs:						
Physocarpus malvaceus	1.3	2.5	4.0	0.4	1.0	2.5
Spiraea betulifolia	.1	1.2	3	T	5	.2
Vaccinium globulare	-	1	1.4	—	T	.2
Total shrubs	1.6	4.6	8.0	.5	1.6	3.6
Grasses:						
Agropyron trichophorum	—	.1	2	—	.1	1
Bromus inermis	—	—	.1	—	—	T
Calamagrostis rubescens	6	3.7	2.5	—	1.4	1.6
Dactylis glomerata	—	16.3	9.5	—	3.6	2.3
Festuca arundinacea	—	—	.1	—	—	T
Total grasses	20.0	24.0	18.5	—	5.3	4.1
Total herbs[2]	29.7	29.0	33.5	—	7.1	7.7
Total vascular plants	31.3	33.6	41.5	—	8.7	10.2

[1]T = trace.
[2]May include shrubs under 5 dm tall with less than one-sixth cover in individual plots.

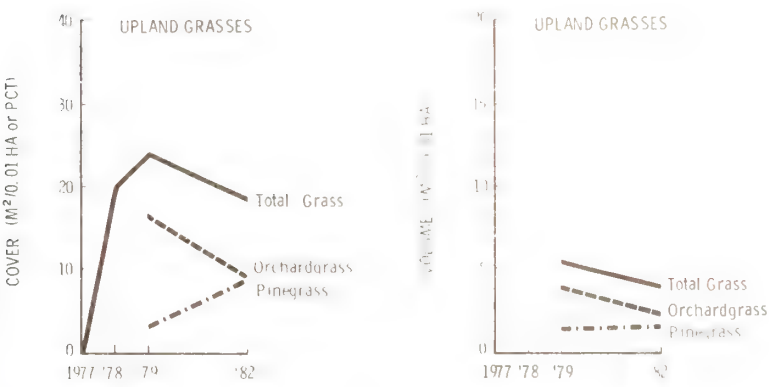

Figure 5.—Cover and volume means for grasses in upland stands. Height measurements were not taken in 1978 for grasses. Soild lines indicate total grass means; dashed lines indicate orchardgrass means; and dashed and dotted lines indicate pinegrass means.

Most of the burned area was aerially seeded; however, one area in the western portion of the burn was not seeded at the request of the landowner. Stand 19 is located in this area and had only a trace of seeded grass in 1978. Other areas without seeded grass were deliberately included in the study so that their development could be followed. Stands 21 and 24, near the eastern and western fire boundaries, did not have any seeded grass present in 1978 and stand 18, well within the burned area, had only a trace amount of seeded grass in 1978.

It seems likely that initially the seeded grasses would compete most strongly with other herbaceous vegetation and seedlings of all species. Data from the four stands originally without seeded grasses in figure 6 contrast with the data from the stands where seeded grasses established well. Seeding did produce high herbaceous cover in 1978 and 1979 (fig. 7). Herbaceous cover has declined somewhat from 1979 to 1982 while cover of seeded grasses has declined more rapidly. In 1979 seeded grasses comprised 71 percent of the herbaceous plant layer; in 1982 they had declined to 45 percent of the herbaceous plant cover in those stands with seeded grasses initially. The stands without seeded grasses initially had lower herbaceous cover values in 1978 and 1979 but they had somewhat higher cover values than stands with seeded grasses in the summer of 1982 (fig. 8).

Tree regeneration data from vegetation plots in upland stands is summarized in table 6. In 1982, seedlings outside the plots were observed in all stands listed in table 6 except stands 15 and 16. A few larch trees survived the fire in the area of stand 21 and there are some larch seedlings in the area as well as lodgepole pine. Stands 20 thru 27 have lodgepole pine seedlings in the stand.

Figure 7.—The highest cover values for seeded grasses on upland sites in 1978 were found in areas similar to stand 15. The dominant grass is orchardgrass; however, the grass in bloom is native pinegrass.

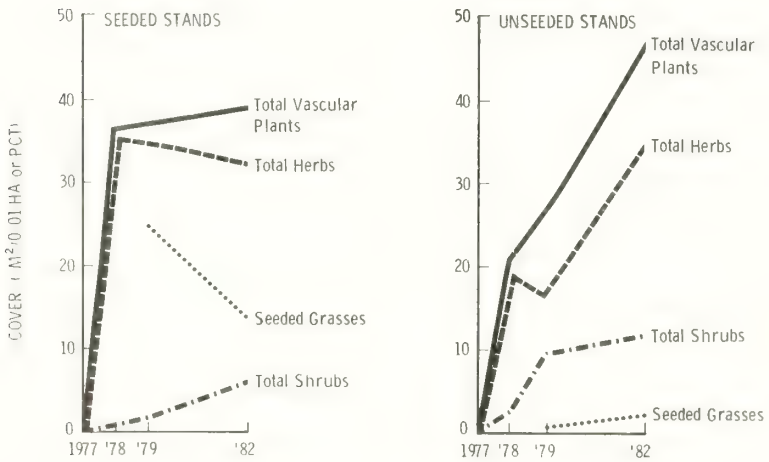

Figure 6.—Cover changes (percentage) for upland stands with seeded grasses initially and those without seeded grasses initially. Solid line indicates total vascular plant cover. Dashed line indicates total herb cover (may include low shrubs under 5 dm with less than one-sixth plot cover). Dashes with dots indicates total shrub cover and dots indicate seeded grass cover.

Figure 8.—Stand 24 on the west edge of the fire is an example of an area that did not have seeded grass initially. (a) Stand 24 in July 1978; (b) stand 24 in August 1982.

Table 6.—Conifer regeneration as counted in herbaceous vegetation plots within Pattee Canyon stands. Plot area is 6 yd^2 (5 m^2) per stand. Species unknown except as indicated (PSME = *Pseudotsuga menziesii*; PICO = *Pinus contorta* and LAOC = *Larix occidentalis*)

Stand	Vegetation plots			
	1978 spring	1978 summer	1979 summer	1982 summer
	Number of seedlings			
15	—	—	—	1 PSME
16	1	—	—	—
20	2	1	—	3 PICO
21	13	7	2	3 PICO
23	2	—	—	2 PSME
24	2	1	1 PSME	10 LAOC 1 PSME
25	2	—	—	1 PSME 1 PICO
26	5	—	—	4 PSME
27	1	—	—	—

VEGETATIVE RECOVERY ON RAVINE SITES

Field methods and data analysis on ravine sites. Thirteen burned ravine stands were selected for study in addition to the unburned ravine stand cited earlier. All stands were sampled in August and September of 1978 and 1979, and eight of the stands were resampled in 1980. During August and September of 1982, all burned ravine stands were resampled except for stands 10 and 14 which have been dropped from the study due to postfire disturbance.

The ravine study used the permanent nested plot design as described by Stickney (1980). Grass nomenclature follows Hitchcock and Chase (1950) other vascular plant nomenclature follows Hitchcock and Cronquist (1973). Data analysis was the same as described for the upland study. Ravine stands are numbered 1 to 14. The physical features of these stands are listed in table 4 and their locations are shown in figure 4. Appendix A-2 lists cover values for ravine species in individual ravine stands each year the stand was sampled.

Study results on ravine sites. Ravines are compositionally far more heterogeneous than any of the upland areas. Variation and shifts in vegetation are abrupt and frequent, whereas on the open slopes shifts appear to be more gradual. The most conspicuous source of this variation is the moisture gradient from the streambed itself to the adjacent side slopes of the ravine. A generalization of this gradient in a moist ravine is depicted in figure 9. Some of the more common plants associated with this gradient are listed in table 7. This moisture gradient continues on up the side slopes to the ridgetop.

Plot placement was subjective and generally attempted to parallel the axis of the ravine in either zone 2 or zone 3. In narrow ravine areas stream curvature may introduce some elements of zone 1; examples are found in stands 5 and 14.

In higher dry ravines without summer overland flow this gradient disappears. Plots in stands 8, 9, and 10 were placed in different areas of the same upper dry ravine in order to represent some of the variation present in those ravines.

Table 8 contains cover and volume means for the seral community life-forms and some important species within the ravine sites sampled in 1978, 1979, and 1982. Recovery was generally more rapid than on upland sites and, with the exception of the seeded grasses, most species present in the initial stages of recovery resprouted from root crowns or rhizomes. Growth of these resprouts, both shrub and herbaceous, was rapid and by the summer of 1978 the ravines as a whole had 77.4 percent vascular plant cover with 90 percent of that cover resulting from native species.

By 1982 shrub cover in the burned ravine stands was 77 percent of that in unburned ravine stand 7. Serviceberry and Rocky Mountain maple in the unburned stand were very tall so that shrub volume in the burned stands was only 40 percent of the unburned stand.

Tree regeneration in the ravines has been minimal. Mature larch and Douglas-fir survived the fire in stands 5, 11, and 12 and in the ravines above stands 6 and 14. An inspection of the slopes near stand 5 in 1980 revealed larch seedlings, but no seedlings have been observed in the ravine plots except for stand 6, which had three Douglas-fir seedlings within the ½-m^2 plots.

The distribution of seeded grasses in the ravines appears to be related to burn severity, available moisture and whether or not a given area received seed. In

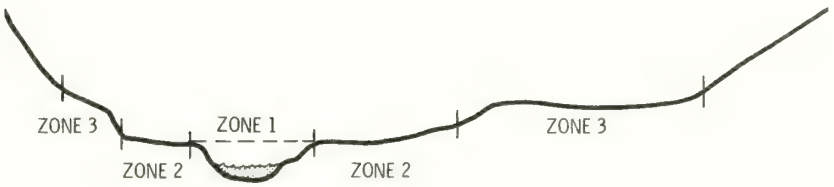

Figure 9.—Gradation across a Pattee Canyon ravine. Some representative species from each zone are listed in table 7.

Table 7.—Species most frequently found in ravine zones identified in figure 9

Zone 1	Zone 2	Zone 3
Mimulus guttatus	*Acer glabrum*	*Physocarpus malvaceus*
Veronica americana	*Mitella stauropetala*	*Acer glabrum*
Veronica serpyllifolia	*Osmorhiza chilensis*	*Calamagrostis rubescens*
Cardamine pensylvanica	*Galium triflorum*	*Aster conspicuus*
Urtica dioica	*Urtica dioica*	*Arnica cordifolia*
Cinna latifolia	*Cinna latifolia*	*Smilacina stellata*
Glyceria grandis	*Glyceria grandis*	*Anaphalis margaritacea*
Athyrium filix-femina	*Symphoricarpos albus*	*Symphoricarpos albus*
	Spiraea betulifolia	*Spiraea betulifolia*
	Rubus parviflorus	*Rubus parviflorus*

Table 8.—*Ravine cover and volume means for ravine stands. Stands 7, 10, and 14 were not visited in all years and are not included in the means*

	Cover			Volume		
	1978	1979	1982	1978	1979	1982
	Percent or m^2/0.01 ha			*m^3/0.01 ha*		
Shrubs:						
Acer glabrum	2.0	5.6	8.9	4.0	10.5	24.2
Amelanchier alnifolia	1.2	2.1	3.5	1.5	4.2	7.0
Physocarpus malvaceus	3.6	6.2	11.5	2.0	5.0	36.9
Rubus parviflora	10.2	13.8	15.5	4.8	8.5	10.1
Spiraea betulifolia	4.8	4.8	3.3	1.6	1.9	1.4
Symphoricarpos albus	5.9	6.7	17.1	3.3	4.1	36.4
Vaccinium globulare	—	.5	.4	—	1	.1
Total shrubs	29.3	43.2	64.1	18.8	38.4	105.3
Herbs:						
Seeded grasses						
Agropyron trichophorum	.1	.6	1.8	.1	7	1.1
Bromus inermis	.1	.5	.8	T[1]	.3	5
Dactylis glomerata	6.0	13.7	10.9	2.4	9.9	3.2
Festuca arundinacea	.1	.7	T	—	—	—
Total seeded grass	7.5	18.1	13.6	2.5	10.9	4.8
Other Herbs						
Aster conspicuus	1.4	2.1	2.0	.6	.9	.6
Calamagrostis rubescens	1.0	2.3	1.3	.4	1.1	.2
Galium triflorum	1.6	2.4	.5	.3	.5	.1
Mitella stauropetala	4	1.8	1.2	T	.1	.1
Osmorhiza chilensis	1.0	1.3	T	.3	.4	T
Total herbs[2]	48.1	51.8	42.8	13.9	23.7	11.9
Total vascular plants	77.4	95.0	106.9	32.7	62.1	117.2

[1] = trace.
[2]May include shrubs under 5 dm tall with less than one-sixth cover in individual plots.

ravines the relationship between burn severity and moisture was of particular importance. In the moist, lower ravines where the fire was severe enough to completely expose mineral soil, the seeded grasses exhibit high cover and volume (fig. 10). In microsites where the ravine was wettest, the fire effects were minimal. In these latter areas natural revegetation by the ground layer plants and the presence of unburned duff prevented establishment of seeded grasses on the ravine floor. In steeper, drier ravines the seeded grass either established well, but did not attain the height or cover in comparison to the moist areas, or was absent altogether.

Table 9 compares stands originally without seeded grasses with the steeper, well-drained sites having seeded grasses and with the moist lower ravines having seeded grasses.

Observations in the moist lower ravines indicate that there were some reductions in low shrubs and native herbaceous species during 1978 and 1979; competition with seeded grasses may have been a factor. Herbaceous species also declined in 1982, which appears to be related to shrub shading in all the ravine stands.

FUEL LOADING ON STUDY AREA

Fuel inventory and analysis. Studies of the fuels during the first 3 years following the fire were done as a second feature of the two primary studies of vegetative recovery. Fuel loading measurements were carried out according to the method recently described by Brown,

Figure 10.—Seeded grass sprouting in June 1978 within one of the severely burned, moist, lower ravines where the seeded grasses did best.

Table 9.—Cover values for seeded grass and the total herb layer (may include some shrubs under 5 dm)

Sites	Year	Seeded grasses	Total herbs	Total vascular plants	Seeded grass/ total herbs
		Percent or m^2/0.01 ha			*Percent*
Ravine stands without seeded grass or with only trace amounts initially	1978	0.2	48.3	85.2	—
	1979	.7	48.4	107.6	1
	1982	1.7	37.8	125.2	4
Well-drained ravine stands with seeded grasses	1978	12.5	44.1	63.4	28
	1979	15.8	42.5	67.5	37
	1982	10.4	34.6	70.3	30
Moist ravines with seeded grasses	1978	14.2	49.5	73.4	29
	1979	41.2	60.8	93.1	68
	1982	30.4	53.1	102.3	57

Table 10.—Average fuel loadings for ravines, uplands, and unburned stands in Pattee Canyon, 1978-80

Fuels	Ravine stands			Unburned ravine stands	Upland stands			All stands		
	1978	1979	1980	1978	1978	1979	1980	1978	1979	1980
Number of plots	54	53	31	4	55	54	33	109	107	64
	Pounds/ft^2 (kg/m^2)									
Dead fuels										
0-1 inch	0.04	0.04	0.04	0.03	0	0.01	0.01	0.02	0.02	0.03
1-3 inches	.09	.07	.08	.09	.03	.02	.04	.06	.04	.06
over 3 inches, sound	.33	.35	.37	.40	.20	.32	.39	.27	.34	.38
over 3 inches, rotten	.07	.06	.06	.04	.04	.01	.03	.06	.04	.04
grass and forbs		.01	.01			.01	.01		.01	.01
shrub	.01							.01		
litter	.01	.02	.02	.05	.03	.01	.01	.02	.02	.02
duff	.57	.56	.49	1.86	.23	.03	.12	.40	.30	.30
Total dead fuels	1.12	1.11	1.07	2.47	.53	.42	.62	.83	.77	.84
	(5.60)	(5.55)	(5.35)	(12.35)	(2.65)	(2.10)	(3.10)	(4.15)	(3.85)	(4.20)
Live fuels										
Grass and forbs	.02	.03	.03		.03	.02	.02	.03	.03	.03
Shrubs	.03	.02	.05	.03		.01	.01	.02	.02	.03
Total live fuels	.05	.05	.08	.03	.03	.03	.03	.05	.05	.06
	(.25)	(.30)	(.40)	(.15)	(.15)	(.15)	(.15)	(.25)	(.25)	(.30)
Total all fuels	1.17	1.17	1.16	2.50	.56	.45	.65	.88	.82	.90
	(5.85)	(5.85)	(5.80)	(12.50)	(2.80)	(2.25)	(3.25)	(4.40)	(4.10)	(4.50)

Oberheu, and Johnston (1982). Fuel plots were located randomly within the stands used for upland and ravine vegetative analysis, rather than randomly across the entire burn. Fuel data were taken for all upland and ravine stands in 1978 and 1979 and for stands 2, 3, 4, 5, 9, 13, 14, 15, 16, 17, 18, 21, 24, and 26 in 1980. Fuel loading sample plot data were analyzed by the USDA Forest Service FUELS computer program (Brown, Oberheu, and Johnston 1982).

Results of fuel study. Fuel loading results for both the ravine and upland sites are presented in table 10. The results show little change in fuels during the first 3 postfire years. Where possible the same plots were use all 3 years; however, it was not always feasible to relocate the exact plots. Some variation in loads betwe years can be attributed to the differences between plot There does appear to be a slight but definite increase i the greater-than-3-inch-sound category, probably cause by falling fire-killed trees. The decrease in ravine duff 1980 was caused by the omission of a wet, lightly burn ed ravine area with high duff levels. The drop in uplan duff in 1979 can not be explained. The seeded grasses have contributed to a rapid increase in the grass and forb category and, following the first year, in the dead grass and forb category.

Generally the fuel loads in ravines are heavier than those on upland sites. For some categories, such as duff, the higher ravine loads can be attributed to the inclusion of relatively unburned areas in the ravine sample. For the live fuels, however, the difference is caused by the more mesic conditions in the ravines.

There were only four fuel plots in the unburned ravine area of stand 7, but they indicate some potential differences in fuels in the grass and forb, duff and litter layers. Under the dense canopy the understory vegetation is sparse. The amount of duff is relatively low in this rather dry ravine and probably comparable to amounts found generally before the fire.

Tree seedling data is also collected in this method. In 1979 seedlings were only found in stand 24, with about 100 Douglas-fir per acre and 100 lodgepole pine per acre. In 1980 lodgepole pine seedlings were found in stand 21 with approximately 1,275 per acre; stand 24 with 200 per acre, and stand 26 with 360 per acre. Larch seedlings were also found in stand 24 in 1980 with 100 per acre. Seedling distribution is very uneven in these plots.

MOSS DEVELOPMENT ON STUDY AREA

Field methods and data analysis. Daubenmire (1970) implies that mosses and lichens are important in preventing wind erosion in Washington steppe and it has also been shown that certain mosses and liverworts are characteristic of newly burned areas (Duncan and Dalton 1982). In Pattee Canyon, bryophytes and lichens were sampled in the same transects used for the permanent vegetation samples (McCune 1978). Both upland and ravine stands were sampled in 1978 and most upland stands were resampled in 1979. Transects were composed of two 25-m segments, with 2- by 5-dm quadrats spaced at 2-m intervals; thus, 25 quadrats were analyzed per plot. Modified Daubenmire (1959) percentages of cover classes were used to evaluate species cover within the quadrats: 0–1 percent, 1–5 percent, 5–15 percent, 15–25 percent, 25–50 percent, 50–75 percent, 75–95 percent, and 95–100 percent. Cover class midpoints were averaged to arrive at a single percentage of cover value for each species for each stand. Nomenclature of mosses follows Crum and others (1973).

Results of moss study. Soon after snowmelt the spring following the fire, mosses and liverworts were apparent on the burn and they continued to spread during the early summer. This bryoid layer was well developed by the September 1978 sample, aided by a cool, moist spring and early summer. On upland sites the principal colonizing species were *Ceratodon purpureus*, *Bryum* spp. (mainly *Bryum caespiticium*), *Funaria hygrometrica*, and *Marchantia polymorpha*. The first two had an average combined cover of 22 percent. They are pioneer species that colonize disturbed soil throughout the Northern Hemisphere. Bryophyte data are summarized in table 11 and found in appendix B.

The fire destroyed mosses and epiphytic lichens throughout the burned area except for a few small areas near the burn perimeter and in some ravines. The same colonizing mosses that were found on upland sites were also found in the ravines, although their cover was generally less in ravines.

Table 11.—Bryophyte cover, 1978-81

Species	Ravines	Uplands		
	1978	1978	1979	1981
	Percent			
Brachythecium spp.	9.6	0.1	0.1	—
Bryum spp.	2.1	7 0	7.2	33.0
Ceratodon purpureus	3.7	15.4	14.6	17.2
Funaria hygrometrica	.1	.6	3	.1
Leptobryum pyriforme	1.3	.3	—	—
Marchantia polymorpha	.7	.4	0	.4
Plagiomnium insigne	5.0	—	—	—
Polytrichum juniperinum	T[1]	.1	T	1.5
Rhytidadelphus triquetrus	1.1	—	—	—
Timmia austriaca	.9	—	—	—

[1]T – trace (less than 0.5 percent).

In 1979, mosses on the upland sites remained generally the same. *Marchantia polymorpha* disappeared, apparently because of the dry summer. Moist ravine sites, which were not revisited by McCune in 1979, did still contain some *Marchantia* in 1979.

In 1981 mosses increased, with *Bryum caespiticium* perhaps increasing at the expense of *Ceratodon purpureus* (table 11). *Polytrichum* also appears to be gaining cover and will probably continue to increase in the future. *Marchantia* reappeared on upland sites and lichens (*Peltigera* sp.) appeared on upland sites for the first time since the fire.

DISTRIBUTION OF CONIFER REGENERATION IN THE STUDY AREA

Sampling methods. In order to determine the relative success of conifer regeneration, seedling data were gathered during the summer of 1980. Transects were established along elevational contours. Four transects were placed completely across the burn at 400-foot (122-m) intervals (at 5,400, 5,000, 4,600, and 4,200 feet elevation; 1 646, 1 524, 1 402, and 1 280 m). A few plots at the western edge of the 4,200-ft (1 280-m) transect are within the area that was salvage logged in 1978. Some partial transects were also run at 4,300 and 4,400 feet (1 311 and 1 341 m) elevation in order to gather more data in the area left unseeded by introduced grasses. Circular,1/300-acre (13.5-m^2) plots were spaced at 328-foot (100-m) intervals along each transect. There were 126 of these seedling plots.

Within each plot, the total number of seedlings of each tree species was recorded. In addition the height and age of the three tallest individuals were recorded. Site variables recorded at each plot included elevation, slope, aspect, duff depth, and indications of soil movement. The presence or absence of standing live or dead trees, and the distance and species of the two nearest potential seed trees (considered if within 150 feet; 46 m) were listed. Presence or absence of understory vascular plants and bryophytes in each plot was recorded.

Results of seedling inventory. The major tree species present before the fire were Douglas-fir, western larch, ponderosa pine, and, above 4,500 feet (1 372 m),

lodgepole pine. Subalpine fir (*Abies lasiocarpa*) is confined to the upper ravines on this site. A few apparently serotinous lodgepole pine stands were located in the upper reaches of the burn.

Tree seedlings on the Pattee Canyon burn occurred with such low frequency that a statistical analysis of the findings would not provide sufficient evidence to warrant projections of tree recolonization. Only 17 of 126 plots actually contained conifer seedlings. Tree seedling data from these plots are in table 12 and maps of the seedling locations are in appendix C. Although good quantitative information is lacking, certain qualitative features of seedling distribution were noted.

Many of the seedlings found were located near the edge of the burn or near islands of live trees within the burn. Some sites were without seedlings despite the close proximity of seed trees. But with few exceptions, plots with seedlings were reasonably close to seed trees. Where dead lodgepole pines with fire-opened cones were found, lodgepole pine seedlings were dense.

Data for understory species with greater than 10 percent total frequency are summarized by elevation (table 13). Spirea and snowberry appear to decrease slightly in frequency with increasing elevation. Ceanothus (*Ceanothus velutinus*) is not common on the burned area but did have 8 percent and 10 percent frequency at 5,000 and 5,400 feet (1 524 and 1 646 m) elevation, respectively. Fireweed shows a decided increase in frequency in the area left unseeded and pinegrass shows a lesser increase in the same area. In addition, the number and percent of plots with evidence of overland flow is listed for each elevation (table 13).

Table 12.—Tree seedling data for Pattee Canyon fire area, 1980

Species	Elevation where present	Number of plots of occurrence	Total number of seedlings	Total number of plots	Number of seedlings/ acre
	Feet (meters)				
Pinus	5,000 (1 524)	5	40	25	1,236
contorta	4,600 (1 402)	2	5	39	38.5
Larix	5,000 (1 524)	1	5	25	60
occidentalis	4,400 (1 341)	1	3	7	128.4
	4,200 (1 280)	2	3	45	20.0
Pseudotsuga	4,600 (1 402)	3	5	39	38.5
menziesii	4,400 (1 341)	1	1	7	42.9

Table 13.—Percentage frequency in tree seedling plots for understory species with greater than 10 percent total frequency and number and percentage of plots with accelerated overland flow. Plots at 4,300 feet and 4,400 feet were in the area that was not seeded

	Elevation in feet (meters)					
Species and flow types	4,200 (1 280)	4,300-4,400 (1 311-1 134)	4,600 (1 402)	5,000 (1 524)	5,400 (1 646)	Total
n =	45	7	39	25	10	126
	Percent					
UNDERSTORY SPECIES						
Shrubs:						
Acer glabrum	15	14	7	12	—	11
Amelanchier alnifolia	11	14	26	20	20	18
Physocarpus malvaceus	51	29	72	44	30	53
Spiraea betulifolia	62	43	46	32	20	47
Symphoricarpos albus	36	57	26	8	—	25
Vaccinium globulare	7	—	5	28	10	11
Grasses:						
Agropyron trichophorum	42	—	—	—	—	15
Bromus inermis	9	14	33	36	20	23
Calamagrostis rubescens	60	86	51	32	—	48
Dactylis glomerata	78	—	49	76	40	61
Forbs:						
Aster conspicuus	29	29	28	16	—	24
Epilobium angustifolium	16	86	38	20	—	26
OVERLAND FLOW						
Number of plots with evident overland flow	4	—	9	8	2	23
Percentage of plots with overland flow	8	—	23	32	20	18

DISCUSSION OF INITIAL VEGETATIVE RECOVERY FOLLOWING PATTEE CANYON FIRE

General Discussion

Early succession vegetation on the Pattee Canyon burn derived from two primary sources: first, the vegetative regrowth of shrubs and perennials, and second, the establishment of artificially seeded grasses. Establishment of annual and perennial herbs or shrubs from natural off-site seed sources was a relatively minor component in the first postfire year (1978). Secondary colonization from some perennials surviving the fire and setting seed became more important in later years.

Although vegetative recovery from the fire was not quantitatively measured until late June and July 1978, casual observations made in late summer and fall of 1977 revealed shrub resprouts along roads and in ravines. Resprouts noted in 1977 included serviceberry, Rocky Mountain maple, ninebark, rose (*Rosa* sp.), and Scouler willow (*Salix scouleriana*) (fig. 11).

Figure 11.—Willow (*Salix scouleriana*) resprouting following the fire.

In April 1978, white spirea and common snowberry (*Symphoricarpos albus*) were resprouting on severely burned sites, along with spring geophytes, conspicuous aster (*Aster conspicuus*), heartleaf arnica, and pinegrass. Less severely burned areas on the eastern edge of the fire exhibited a wider variety of resprouts, including fire-sensitive plants, for example, kinnikinnick (*Arctostaphylos uva-ursi*). Only a few annuals were seen. Slenderleaf collomia (*Collomia linearis*) and blue-eyed Mary (*Collinsia parviflora*) were present and miner's lettuce (*Montia perfoliata*) was conspicuous in many areas. Rapidly sprouting artifically seeded grass was also very conspicuous in most areas. During the spring of 1978, however, much of the burned area was black ash, and resprouts of perennials were scattered. Vegetative cover in ravines was somewhat more dense, but still scattered.

By late June 1978, quantitative sampling began. Artifically seeded grasses were well established and had achieved canopy coverage values of up to 32 to 36 percent in some upland plots. Native pinegrass responded quickly on upland sites and in drier ravine sites. In the ravines, shrub regrowth from rootstocks and rhizomes was already vigorous, with up to 40 percent cover.

Annuals were most common on the burned area the first spring although they were a minor part of the vegetation. In addition to the annuals cited earlier, prickly lettuce (*Lactuca serriola*) established successfully on the burn in 1978. Its height made it conspicuous by summer and, although it achieved greater than 1 percent cover in only one stand, it was present in nine of the ravine stands and 10 of the upland stands.

By August and September 1978, the spring geophytes, early flowering perennials, especially heartleaf arnica, and spring annuals had either disappeared from view or were represented by greatly reduced cover. Summer flowering perennials, including the seeded grasses, and shrubs were close to maximum development for the year.

In 1979, few annuals were present in either upland or ravine plots. May, June, and July of 1979 had less than 50 percent normal precipitation and herbaceous flora on upland sites and in dry ravines decreased slightly in cover. This did not appear to affect the moist ravines.

Lyon and Stickney (1976) describe the characteristic pattern for forest succession in the Northern Rocky Mountains as an initiating herb stage followed in turn by shrub and tree stages. This model of succession uses the dominant life-form rather than vegetation composition as the basis for successional stages and compares the shrub and tree layers with the herbaceous layer. The life-form patterns for the first 2 to 3 years of upland and ravine postfire development in Pattee Canyon are summarized in figures 12 and 13.

By the fifth postfire year (1982) the ravines generally were shrub dominated, although four sites (stands 1, 3, 4, and 8) had only 40 to 47 percent shrub cover. The seven other ravine sites visited in 1982 had 56 to 78 percent shrub cover. While most upland areas are still herb dominated, stand 19 has 51 percent shrub cover.

Recovery of Conifers

In addition to the 1980 study of the distribution of conifer regeneration, tree regeneration data were gathered during the upland study, the ravine study, and while determining fuel loads for the stands in these studies. All these sources of tree regeneration data indicate few seedlings are present and those are clumped near the burn edges, near surviving trees or near serotinous lodgepole pines. The lodgepole pine seedlings that established following the fire have gained sufficient height to be readily visible above herbaceous vegetation by 1982 and are scattered across the burn. Most of the lodgepole pine seedlings observed were above 4,800 feet (1 460 m) elevation but occasional individuals were observed down to about 4,100 feet (1 250 m).

Lodgepole pine regeneration following fire is dependent on a "one show" effort. In the next few years a

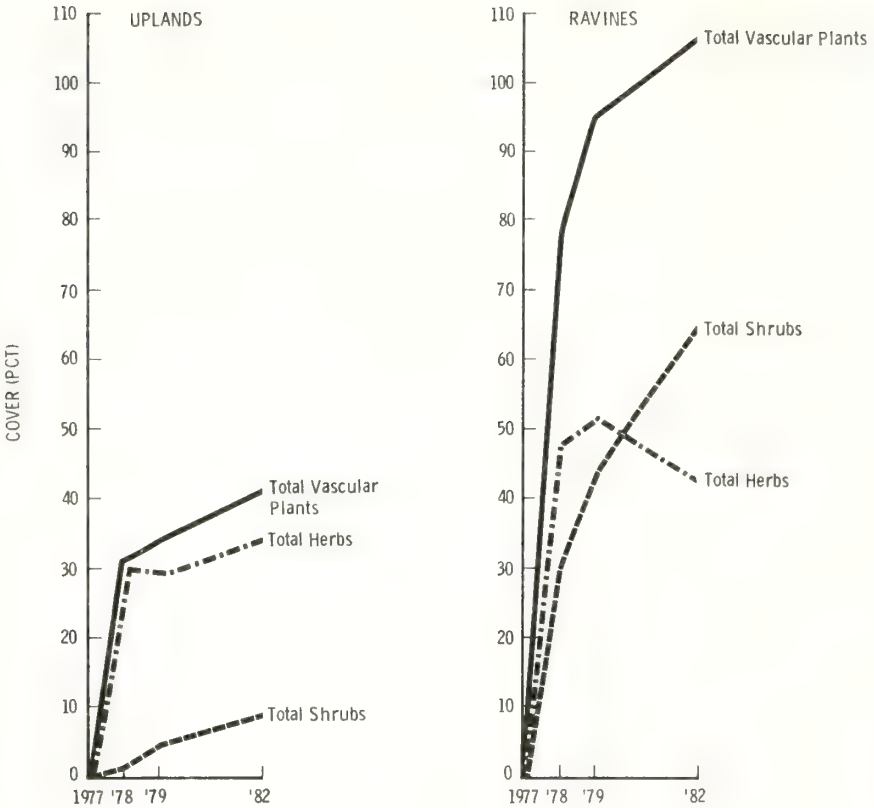

Figure 12.—Upland and ravine cover means for life-forms. Solid lines indicate total vegetative cover; dashed lines indicate shrub cover; and dots and dashes indicate herbaceous cover.

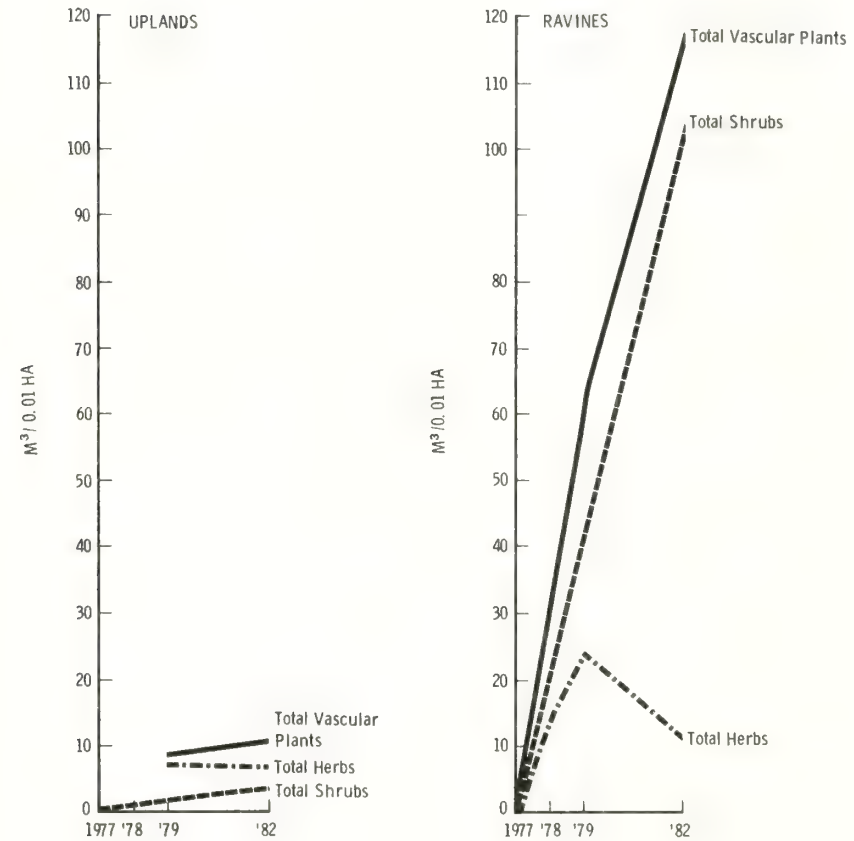

Figure 13.—Upland and ravine volume means for lifeforms. Solid lines indicate all vascular vegetation; dashed lines indicate shrubs; and dashes with dots indicate herbaceous vegetation.

moderate disturbance, such as a light ground fire, could eliminate the present seedling crop. This would diminish dramatically the relative success of lodgepole pine on the burn. With a more constant seed source in the face of moderate disturbance, other conifers could fare better in the long run. Without any disturbance, lodgepole pine's early maturity may allow it to increase in proportion to other species in the developing postfire stand.

Recovery of Individual Understory Species

This discussion of understory species attributes is based on observation and data collected on the Pattee Canyon site only. Species may behave differently on different habitats within the limits of their range.

SHRUB RESPONSE

Of all the shrubs considered, only ninebark, white spirea, and huckleberry have at least 1 percent mean cover on both upland and ravine sites. Thimbleberry, Rocky Mountain maple, common snowberry, and serviceberry are important in the ravines while huckleberry has little cover at present. Serviceberry has shown the most damage from browsing by deer in the first years since the fire. Postfire response of shrubs in Pattee Canyon is shown in table 14. Increases in volume for the most dominant ravine shrubs are shown in figure 14.

Competitive ability in shrubs is frequently related to their ability to spread from rhizomes. Those species that spread from rhizomes tend to show clustered (aggregated) distributions. On the Pattee Canyon burn, patches of blue huckleberry, thimbleberry, and common snowberry are conspicuous. Thimbleberry made a rapid recovery in the first years and then gained volume more slowly up to the fifth year; snowberry recovered more slowly initially and has increased its volume very rapidly in the third to fifth year interval. Spirea is more uniformly distributed; it resprouted quickly, maintained nearly the same cover during 1979 and 1980, but subsequently has declined in most areas.

Resprouts of blue huckleberry were few in 1978, increased somewhat in 1979, and then increased more by 1982 on upland sites. Miller (1977) states that the depth of heat penetration controls the number of *Vaccinium globulare* resprouts. Density increases if stems are killed just below ground level, so that sprouts appear from rhizomes; however, density decreases if heat kills the shallow rhizomes and sprouting occurs from deeper levels with fewer rhizomes. The Pattee Canyon fire was severe in many areas and blue huckleberry's recovery was slow. All plants sampled in ravine patches of resprouting blue huckleberry during 1980 were sprouting from lateral rhizomes located at depths of 3.5 to 6 inches (9 to 15 cm).

Table 14.—Postfire behavior of some Pattee Canyon shrubs

Species	Fire survival	Seed production	Expansion potential
Physocarpus malvaceus	Root crowns	Occasional plants flowered in 1980 most plants flowered in 1981	Appears to be slow
Acer glabrum	Root crowns	Did not set seed in the 1st 3 postfire years. Did have seeds by the fifth summer	Has winged samara
Spiraea betulifolia	Rhizome	Set seed the first year following the fire	Can spread vegetatively by rhizomes and has early seed production
Symphoricarpos albus	Rhizome	Some fruit the first postfire year	Vegetative spread by rhizomes; bird carried seed
Vaccinium globulare	Both shallow and deep rhizomes	Fruit the third postfire year	Vegetative spread by rhizomes; bird carried seed
Amelanchier alnifolia	Root crowns	Fruit the second postfire year	Animal carried seed
Rubus parviflorus	Rhizomes	Fruit the first postfire year	Spreads vigorously by rhizomes; bird carried seed

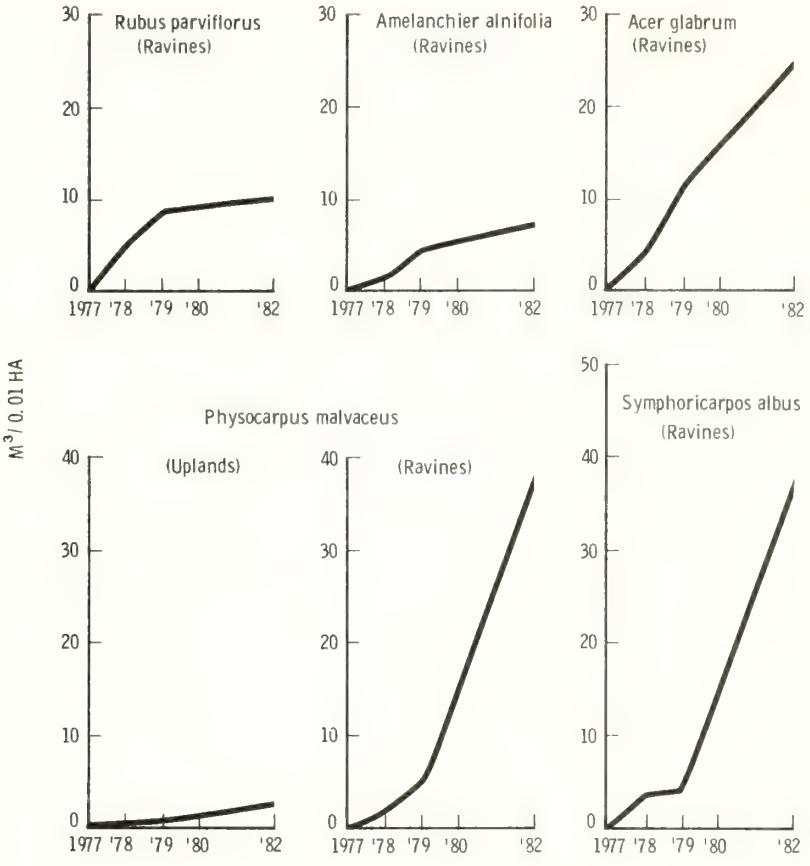

Figure 14.—Volume changes for dominant shrub species since the fire. Solid lines indicate volume in all ravine stands. Volume = 1 dm³/0.01 ha.

HERBACEOUS SPECIES RESPONSE

The most abundant native species on the burn is pinegrass. Pinegrass maintains itself in dense forest shade but only produces seed in forest openings. Spring and summer regrowth and spread in 1978 were from rhizomes. It also bloomed profusely during the summer of 1978 (fig. 15) and seedlings were observed during the 1979–1981 seasons. Cover increases in 1982 may reflect this new growth. Postfire behavior of pinegrass and some other herbs is found in table 15.

Common fireweed (*Epilobium angustifolium*) is widely distributed on the burn with low mean cover values of less than one percent. It resprouted from roots (sometimes considered as rhizomes) during spring of 1978 in many ravines and possibly on upland sites. Blooming the first season was profuse on the scattered surviving plants, producing light, wind-blown seeds.

Both heartleaf arnica and broadleaf arnica (*A. latifolia*) are present on the burn. Heartleaf arnica is more generally distributed, while broadleaf arnica is restricted to ravine side slopes. Conspicuous aster is also rhizomatous, with wind-blown seeds. The arnicas form clumps similar to those produced by rhizomatous shrubs and have dispersed little otherwise; the aster is more generally distributed and forms only small clumps.

Two other widely distributed ground layer species are creeping Oregon-grape (*Berberis repens*), a low subshrub considered in this study with the herbaceous layer, and western meadowrue. They are stoloniferous or

Figure 15.—Pinegrass in bloom during summer 1978.

Table 15.—Postfire behavior of some Pattee Canyon herbs and mosses

Species	Fire survival	Seed production	Expansion potential
Perennials:			
Arnica cordifolia *Arnica latifolia* *Aster conspicuus*	Rhizomes	Seed set the first year	Some vegetative spread from rhizomes; wind-carried seeds
Berberis repens	Stolons	Few flowers the first postfire year more the second	Bird carried fruit
Calamagrostis rubescens	Rhizomes	Bloomed profusely the first postfire summer; continued blooming succeeding years	Good recovery from both rhizones and seed
Epilobium angustifolium	Rhizome-like roots and wind carried seed	Began blooming profusely the first postfire summer	Some vegetative spread from rhizomes; wind-carried seed
Galium triflorum	Shallow, fine rhizomes; survived in moist areas	Bloomed the first postfire year	Small, barbed seeds carried by animals; limited expansion
Geum macrophyllum	Short root stocks	Bloomed the first postfire year	Spread limited to moist ravines
Linnaea borealis	Creeping stems; only in sheltered microsites	Not observed	Vegetative spread by creeping stems
Mimulus guttatus	Short stolons along side streams	Bloomed the first postfire year	Expanding into newly shade-free stream-side sites
Osmorhiza chilensis	Short, shallow roots	Bloomed the first postfire year	Barbed seeds carried by animals
Pyrola secunda	Slender rhizomes in sheltered microsites	Not observed	Possible seedling; source unknown
Urtica dioica	Strongly rhizomatous; moist sites	Bloomed the first postfire year	Vegetative spread; possibly seedlings
Annuals:			
Corydalis aurea *Geranium bicknellii*	Possibly soil-stored seed	Bloomed and set seed first postfire year	Almost disappeared the second postfire year
Lactuca serriola	Off-site wind-blown seed	Set seed first year	Almost disappeared the second postfire year
Mosses:			
Bryum caespiticium *Ceratodon purpureus*	Light off-site wind-blown spores	Produced few spores late the first postfire year; many the second	By wind-carried spores; vegetative expansion

hizomatous and have low cover values, especially on pland sites, following the 1977 fire.

Spring ephemerals with deep corms or rhizomes were sually present in sampling plots as dead stalks or litter y late summer. Lambstongue fawnlily (*Erythronium randiflorum*) is common across the burn. Casual obser-ations indicate that it sprouted and bloomed in 1978; owever, in the spring of 1979 and 1980 lambstongue awnlily flowers were spectacular across the burn.

Sweetscented bedstraw (*Galium triflorum*) is found rimarily in ravines. Shallow, fine rhizomes along with mall, barbed seeds allow it to persist and spread in uch areas. Mountain sweetroot (*Osmorhiza chilensis*) ersists from rootstocks, has barbed seeds, and does est in moist ravines. Both had the highest cover values 1 1979, the second summer after the fire, and have eclined in cover since.

Largeleaf avens (*Geum macrophyllum*), common onkeyflower (*Mimulus guttatus*), and stinging nettle *Jrtica dioica*) apparently expanded their populations in oist ravines since the fire; however, they are primarily ound on the moistest sites and were not quantitatively ampled in plots. Stinging nettle, particularly, appears o thrive on disturbance, although its rate of spread ollowing the fire may have been slowed by competition from orchardgrass combined with an infestation of caterpillars in 1979 and 1980.

A few species present the first summer after the fire possibly were present as buried seed before the fire. Examples include Pennsylvania bittercress (*Cardamine pensylvanica*), golden corydalis (*Corydalis aurea*), dragonhead (*Dracocephalum parviflorum*), and Bicknell geranium (*Geranium bicknellii*). Since the first postfire year Pennsylvania bittercress has been observed on exposed sites following spring flooding; golden corydalis has disappeared completely; and both American dragonhead and Bicknell geranium have occasionally been observed in trace amounts. Prickly lettuce (*Lactuca serriola*) was the only annual with wind-carried seed that established in enough quantity to receive a cover value in any plot in 1978.

Rowe (1979) considers creeping subshrubs to be fire avoiders. Sidebells shinleaf (*Pyrola secunda*) and kinnikinnick are in this classification; nevertheless, both were present on the burn by the first summer, mainly as occasional resprouts in sheltered microsites. Pyrola seedlings were also found in one of the drier ravine sites during 1979. In contrast, princes pine (*Chimaphila umbellata*) was present in this area, according to Schuler (1968), and has not been observed on the burn since the fire.

MOSS RESPONSE

The dominant species of moss colonizing the burn immediately following the fire resulted from spores (table 15) borne by the wind from off site sources. Such mosses initially spread vegetatively. Spores survived and germinated best in sheltered microsites. The liverwort *Marchantia polymorpha* also colonized the burned area although it was infrequently found in Pattee Canyon prior to the fire (McCune 1978). Propagules may have come from residual *Marchantia* populations in moist ravines for the initial colonizing populations in 1978 and the recolonizing populations in 1980.

Response of Seeded Grasses

The four perennial grasses seeded on the burn are either bunchgrasses or sodforming grasses. Orchardgrass established best and has been the major species of seeded grass present in all burn areas. When these grasses were seeded, it was anticipated that orchardgrass would be the strongest competitor and that it would be naturally lost from the site in 10 years, or at most in 20 to 25 years. Seedlings of orchardgrass were present in 1981, indicating some ability to reproduce on this site. Wheatgrass (*Agropyron trichophorum* and *A. intermedium*) has increased its (low) canopy cover since 1978. It has not been determined if this is the result of seedling production.

COMPETITION BETWEEN SEEDED GRASSES AND NATURAL REVEGETATION

The competitive impact of orchardgrass has been strongest and most obvious in the moist, lower ravines. In these areas the orchardgrass has grown very lush and tall, shading and suppressing low shrubs and other herbs. Conversely some plots were observed where orchardgrass and other seeded grasses were shaded and evidently retarded by the vigorous regrowth of resprouting tall shrubs.

The impact of grass seeding on upland sites is not so easily observed. Data suggest that seeded grasses compete and may suppress other species. The grasses shade other vascular plants and compete for nutrients and moisture by aggressive fibrous roots. There is at present insufficient conifer regeneration to reach any conclusions about the impact of orchardgrass on conifer regeneration. In his discussion of the moss layer, McCune (1978) stated that "the herbaceous layer (orchardgrass and pinegrass) sufficiently moderated the microclimate near the ground to allow more survival of the young mosses during dry periods." By 1981, however, mosses were becoming buried in the grass litter and spore production was high (McCune 1981; personal communication).

EROSION CONTROL

Erosion control was a primary purpose for the grass seeding project in the Pattee Canyon burn. Our studies were not, however, designed to moniter erosion, nor were they designed to evaluate the effect of seeded grasses on erosion. Casual observations by study participants indicate that accelerated erosion was not apparent during the first 2 postfire years.

During late May of 1980, several days of above normal rainfall resulted in the flooding of Pattee Creek. Visual inspection of the burned area following the flooding indicated that some soil movement did occur on the steep upper slopes, especially between clumps of orchardgrass and other vegetation. The lower slopes, however, showed little or no apparent erosion. The unseeded area (fig. 3) showed no apparent evidence of erosion following the 1980 storm. Further comments on the benefits of seeding grasses are found in Crane and Habeck (1982).

WILDFIRE HAZARD

Wildfire hazard in the burned area has changed drastically as a result of the fire and subsequent grass seeding. Removal of the forest canopy and most downed woody surface fuels by the fire has eliminated the probability of moderate-to-severe fires for many years to come. The probability of a fast-spreading, low-intensity surface fire does exist as a result of the grass seeding. A nearly continuous mat of dead grass covers most of the burned area. During late summer, after the current year's crop of grass cures, a fire could sweep the area. The result of such a fire would be to set back tree and shrub revegetation.

Summary

On the Pattee Canyon burn the initial vascular vegetation is derived from two main sources; preburn vegetation and seeded grass. (1) At present the most competitive species appear to be orchardgrass and pinegrass with orchardgrass presently dominant in most areas. (2) In ravines and those upland sites with prefire shrub cover the shrubs have achieved dominance fairly rapidly. (3) It appears, however, that secondary colonization by shrubs will be necessary on many upland sites in the burned area before a shrub stage as defined by Lyon and Stickney (1976) could occur. (4) The recovery of understory plants has been much more rapid in the ravines than on any upland sites. (5) Tree regeneration is at present scarce on most of the burn. Given the distance from seed trees to much of the burned area, it appears that regeneration of conifers may be very slow.

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APPENDIXES A-1 and A-2

(see fold-out at end of publication)

Composition and percent cover of bryophyte and lichen component within Pattee Canyon ravine communities, 1978. T = trace cover.

Species	Stand number													
	1	2	3	4	5	6	8	9	10	11	12	13	14	7
	Percent or m^2/0.01 ha													
Bryophytes														
Atrichum selwynii	–	–							T			–		–
Aulacomnium androgynum														T
Brachythecium spp.					21.4	16.5			8.8	28.8	16.6		27.2	15.1
Bryum spp.	2.3	1.1	3.9	4.5			5.2	8.1	1.4	.8	T	2.5		
Campylium chrysophyllum													.1	
Ceratodon purpureus	1.6	.9	2.1	5.0		5	31.7	3.7	8	.2	T	4.7		
Dicranum scoparium						1							T	.1
Dicranum tauricum						1							T	.3
Drepanocladus uncinatus											4		.1	1
Eurhychium purchellum														.4
Funaria hygrometrica	.2	.1	3	2			5	3	T	T		2		
Leptobryum pyriforme							4.7	2.3	10.8			.5		
Marchantia polymorpha			.5	1.0			7.2	.5	T	T				.1
Mnium spinulosum						4					1		.2	.8
Plagiomnium insigne					55.4	8.2				6	2.1		3.3	T
Pleurozium schreberi						T								2.5
Pogonatum alpinum							4							
Pohlia cruda									T					T
Pohlia nutans												–		
Polytrichum juniperinum	.1	T	T	T				1	1		T	.1		
Ptilium crista-castrensis						T						–		
Rhizomnium spp.						4.4				T	.1	–	4.1	
Rhytidadelphus triquetrus					2.6	10.2						–	.5	1.9
Timmia austriaca						3.3	T		T		T	T		9.3
Tortula ruralis												–	–	
Lichens														
Peltigera canina	–	–				.1			.4		1.2	–		.4
Peltigera leucophlebia		–			–				–	–	.1	–	–	1.3
Peltigera malacea		–				T			T	–		–	–	–
Peltigera spuria	–	–			–		–		T			–	–	–
Total number of species	4	4	5	5	3	13	7	6	13	7	11	6	9	15

Composition and percent cover of bryophyte and lichen component within Pattee Canyon upland communities.

Species	Stand 15 78	15 79	15 81	16 78	16 79	16 81[1]	17 78	17 79	17 81	18 78	18 79	18 81	19 78	19 79	19 81	20 78	20 79	20 81
	Percent or m²/0.01 ha																	
Bryophytes																		
Atrichum selwynii	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Brachythecium albicans	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Bryum caespiticium	1.6	–	19.1	11.0	5.2	16.4	7.0	2.3	31.0	5.7	5.8	36.0	12.4	18.2	46.1	3.4	3.5	–
Ceratodon purpureus	43.1	–	30.0	7.5	9.6	18.8	30.0	34.3	8.6	3.4	2.7	6.8	10.6	37.2	24.9	4.9	5.9	–
Dicranum scoparium	–	–	T	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Funaria hygrometrica	1.6	–	–	1.1	T	.5	1.2	2.3	.2	.2	T	–	–	1.2	.7	.1	–	–
Leptobryum pyriforme	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Marchantia polymorpha	.1	–	–	.3	–	T	T	–	–	.2	–	–	–	–	–	T	–	
Minum spinulosum	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Pogonatum alpinum	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
Polytrichum juniperinum	T	–	.1	.2	–	1.9	–	–	.2	.2	1	2.0	–	–	.4	–	–	–
Tortula ruralis	–		–	T	–	T	–		–		–	–	–	–		–	–	
Eurhynchium pulchellum	–	–	–		–	–	–	–	–			–	–	–	–	–	–	
Lichens																		
Cladonia sp.	–	–	–	–	–	–	–		–	–	–	–		–		–	–	
Peltigera canina	–	–	–	–	–	T	–	–	–		–	–	–	–	–		–	–
Peltigera leucophlebia		–	–	–		–	–	–	–	–				–	–	–	–	–
Peltigera spuria	–		.1	–	–	T		–		–	–	.3		–	.2	–	–	
Total number species	5	–	5	6	3	8	4	3	4	5	4	4	2	3	5	4	2	–

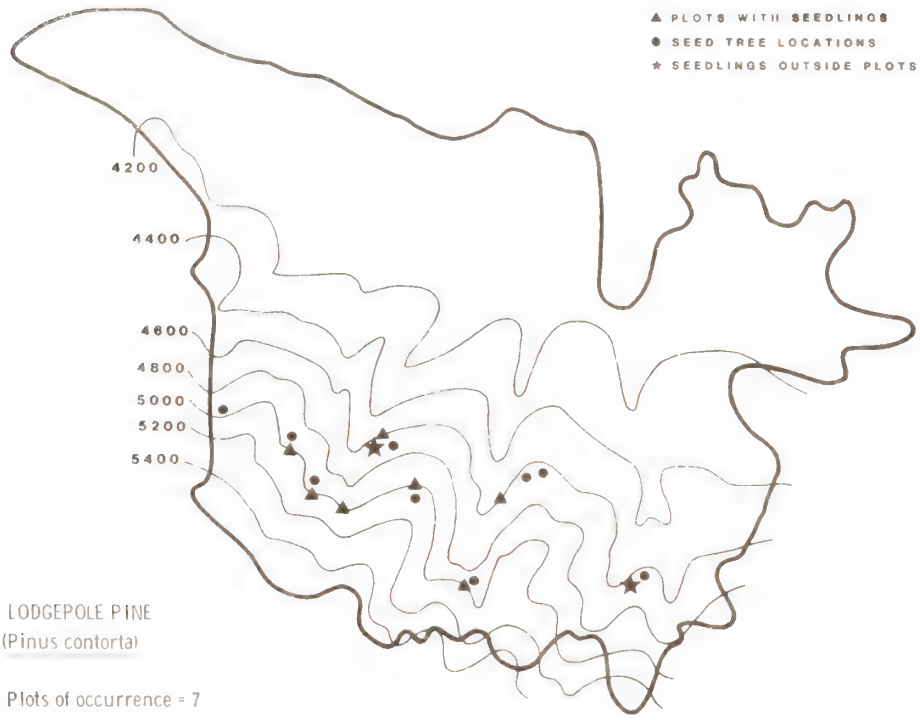
(con.)

Species	Stand 21 78	21 79	21 81[1]	22 78	22 79	22 81[1]	23 78	23 79	23 81	24 78	24 79	24 81[2]	25 78	25 79	25 81	26 78	26 79	26 81	27 78	27 79	27 81[2]
	Percent or M²/0.01 ha																				
Bryophytes																					
Atrichum selwynii		–		0.1		–	–	–	–										–	–	–
Brachythecium albicans	–	–	–	1.2	.6		–	–	–	–	T	–	–		–	–	–	–	–	–	–
Bryum caespiticium	3.5	1.6	20.8	2.5	5.3	14.2	20.3	9.2	65.5	1.3	1.7	30.7	15.2	24.5	58.0	3.1	2.5	22.3	5.1	6.7	35.3
Ceratodon purpureus	23.5	15.0	33.1	8.8	10.0	12.0	38.2	25.8	1.6	0.5	1.2	19.8	5.5	5.8	12.0	18.7	21.5	23.4	5.5	6.4	15.8
Dicranum scoparium	–	–	–	–	T	–		–	–	–	–	–	–		–	–	–	–	–	–	–
Funaria hygrometrica	1.1	.4	T	.4		–	1.3	.1	–	T	–		.2	T	–	.5	.1	–	.4	T	T
Leptobryum pyriforme	3.2	–	–	.3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Marchantia polymorpha	1.1	–	.3	.6	–	.2	1.8	–	–	T	–	–	1.2		4.1	.2	–	.1	.1		–
Minum spinulosum		–	–	–	T	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Pogonatum alpinum	T	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Polytrichum juniperinum	.3	.1	.8	.4	T	4.6	.1	T	.7	T	T	.1	.1	.1	2.8	.1	T	2.3	0.3	T	2.5
Tortula ruralis		–	–	–	–	–	–	–		–		–	–	–	–		–	–	–	–	–
Eurhynchium pulchellum	–		–					–	T		–	.5		–		–	–		–	–	–
Lichens																					
Cladonia sp.				T		–		–	–	–					–	–			–	–	–
Peltigera canina	–		T	.6			–	–	–	–	–	–	–	–	–	–	–		–	–	
Peltigera leucophlebia	–		–	.1	–	–	–	–	–	–		–	–	–	–	–	–	–			
Peltigera spuria	–	–	1.0	T		–	–	–	–	–		.4			T			.8	–	–	–
	7	4	7	12	6	4	5	4	4	5	4	5	5	4	5	5	4	5	5	4	4

[1]1981 data for stands 16, 21, and 22 based on one transect only (the second one was not found)
[2]Position of one transect each in stands 24 and 27 is approximate as the stakes were not found in 1981.
T = trace

APPENDIX C

Maps showing tree distribution for each of the major tree species present on the burn. Triangles indicate plot locations where seedlings of that species are present within the plot. Circles indicate plot locations where seed trees of that species were present, and stars indicate the locations of seedlings noted along the transect but not actually within a plot.



LODGEPOLE PINE
(Pinus contorta)

Plots of occurrence = 7

PONDEROSA PINE
(Pinus ponderosa)

Plots of occurrence = 0

APPENDIX A-1

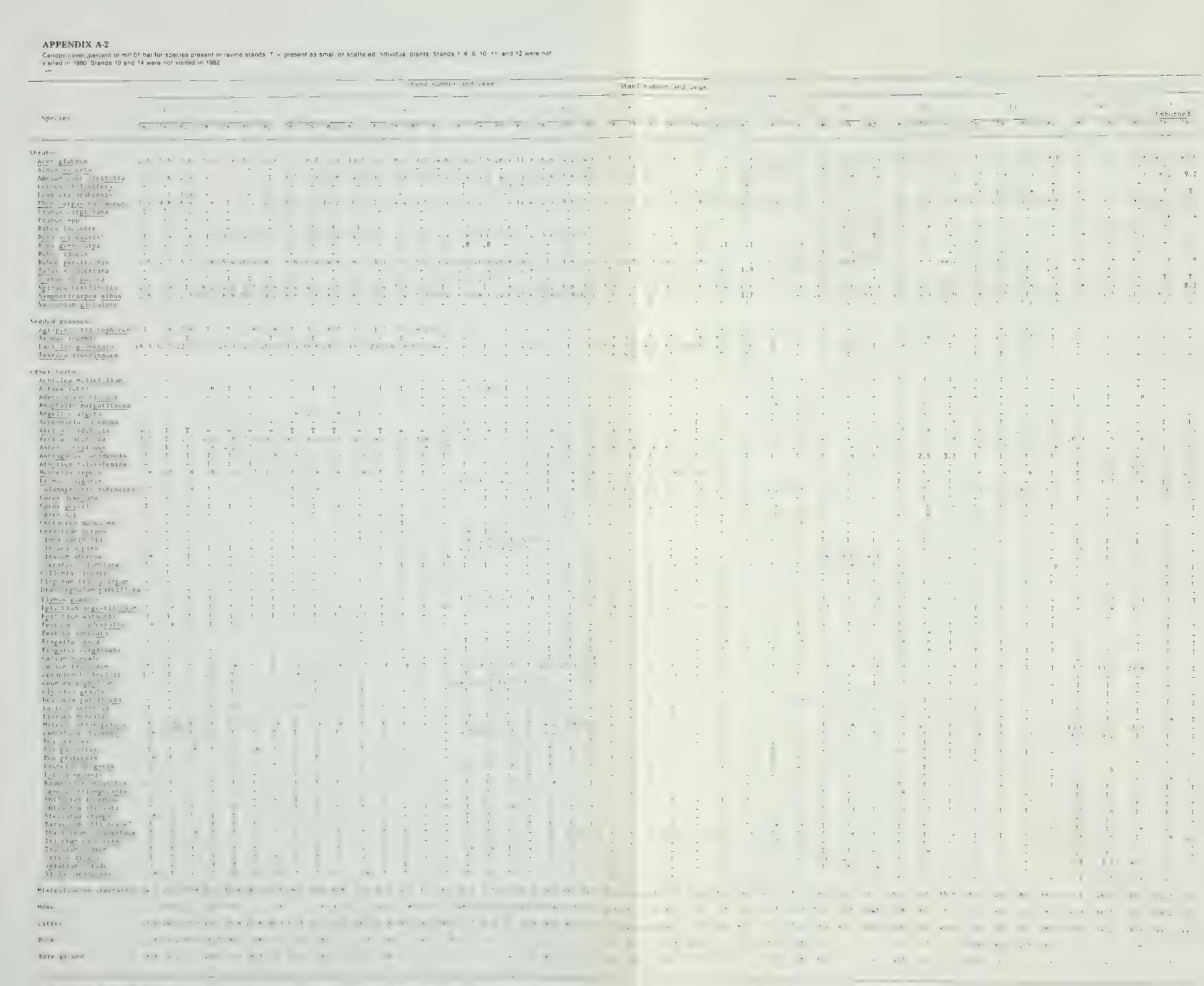
Canopy cover (percent or m^2/.01 ha) for species present in upland stands T = present as small or scattered individual plants

Species	Stand number and year																																				
	15			16			17			18			19			20			21			22			23			24			25			26			27		
	78	79	82[1]	78	79	82	78	79	82	78	79	82	78	79	82	78	79	82	78	79	82	78	79	82	78	79	82	78	79	82	78	79	82	78	79	82	78	79	82
	Percent or m^2/.01 ha																																				
Shrubs																																					
Amelanchier alnifolia	-	-	-	-	-	.8	-	-	.8	-	T	1.9	-	-	.5	-	-	2.5	T	0.8	1.0	-	-	-	-	-	.8	-	-	-	-	-	.8	-	T	.8		
Physocarpus malvaceus	T	T	1.3	-	-	-	5.0	3.3	14.0	0.8	2.5	.8	9.2	19.2	24.7	-	-	-	T	1.7	2.5	2.5	1.7	5.6	T	1.7	2.7	T	-	.8	T	-	T	-	-	-	-	T	-
Rosa gymnocarpa	-	-	-	-	-	-	-	-	-	-	-	-	T	3.3	1.5	T	T	T	T	0.8	1.7	-	-	-	-	-	-	-	-	-	-	-	.8	-	-	-		
Salix scouleriana	-	-	-	-	-	-	-	-	-	-	-	T	-	-	-	-	-	-	T	0.8	.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
Spiraea betulifolia	4.2	8.3	2.5	-	T	-	T	.8	-	0.8	3.3	1.7	T	.8	.8	T	.8	.8	T	3.3	3.3	-	-	-	-	4.2	3.3	T	T	.1	T	.8	.8	T	.8	T	T	-	-
Symphoricarpos albus	-	-	-	-	-	-	T	T	1.7	-	T	T	0.8	2.5	1.3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
Vaccinium globulare	-	-	-	-	T	2.5	-	-	-	-	-	-	-	-	-	-	.8	3.3	-	-	4.2	-	-	-	-	.8	.8	-	-	T	-	-	.8	-	T	5.0	-	-	T
Grasses																																					
Agropyron trichophorum	-	.8	T	-	-	T	-	-	.8	-	1.7	1.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bromus inermis	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.8	-	-	-	-	-	-	-	-	-	-	-	-	-	.8
Calamagrostis rubescens	-	3.3	.8	-	10.8	15.8	-	-	5.8	-	9.2	19.2	-	4.2	14.2	-	.8	4.2	6.7	10.8	10.0	-	1.7	3.3	-	5.8	8.3	-	.8	11.7	-	-	-	-	-	2.5	-	-	6.7
Dactylis glomerata	-	34.2	14.2	-	19.2	17.5	-	35.8	22.5	-	-	4.2	-	.8	.8	-	43.3	10.0	-	-	-	-	21.7	13.3	-	12.5	4.2	-	-	2.5	-	26.7	24.2	-	27.5	6.7	-	8.3	7.5
Festuca arundinacea	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	T	-	-	T	-	-	1.7	-	-	T	-	-	T		
Festuca occidentalis	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grass spp.	40.8	2.5	-	10.8	1.7	-	33.3	5.0	-	-	.8	-	2.5	-	-	40.0	.8	-	6.6	-	-	36.7	9.2	-	5.8	5.0	-	-	.8	-	40.8	10.0	-	34.2	-	-	22.5	12.5	-
Total Grass	40.8	40.8	15.0	10.8	31.7	33.3	33.3	40.8	29.1	-	11.7	25.1	2.5	5.0	15.0	40.0	45.0	14.2	13.3	10.8	10.8	36.7	32.6	17.4	5.8	23.3	12.5	-	1.7	14.2	40.8	36.7	25.9	34.2	27.5	9.2	22.5	20.8	15.0
Other herbs																																					
Antennaria racemosa	-	-	-	-	T	T	-	-	-	-	-	-	T	-	-	-	-	-	.8	2.5	2.5	-	-	-	-	-	T	-	T	.8	-	-	-	-	-	T	-	-	-
Arnica cordifolia	T	T	T	T	T	T	T	T	T	1.7	T	T	1.7	T	T	5.0	T	5.8	T	T	1.7	T	T	.8	5.0	T	.8	T	T	T	-	-	-	T	T	T	T	T	T
Aster conspicuus	-	-	-	-	-	-	T	T	.8	-	-	T	T	T	T	-	T	-	-	-	-	3.3	T	10.8	-	.8	.8	-	T	T	-	-	-	-	-	-	-	-	T
Astragalus miser	T	-	-	-	-	-	T	-	-	-	-	-	.8	T	-	-	-	-	-	-	-	-	-	-	-	-	-	-	T	-	-	-	-	-	-	-	-	-
Berberis repens	0.8	.8	.8	-	-	-	1.7	2.5	5.0	-	-	-	T	1.7	T	-	-	-	-	-	-	-	-	-	-	-	-	-	T	-	-	-	-	-	-	-	-	-
Carex geyeri	-	-	-	T	0.8	-	-	-	-	-	T	T	-	T	.8	-	-	-	-	-	-	T	-	-	-	-	-	-	-	-	-	-	T	T	-	-	T	-	-
Centaurea maculosa	-	-	-	-	-	T	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.8	-	-	-	-	-	-	-	-
Clematis columbiana	-	-	-	-	-	-	-	-	-	-	-	-	T	T	.8	-	-	-	-	-	T	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Epilobium angustifolium	T	T	T	T	T	.8	T	-	-	1.7	8.3	5.0	T	T	T	T	T	T	T	T	T	T	T	T	-	-	-	.8	2.5	1.7	T	-	1.7	T	-	T	T	T	T
Fragaria virginiana	-	-	-	-	-	T	-	-	-	-	-	-	-	-	-	T	-	-	T	.8	T	-	-	-	-	-	-	T	T	T	-	-	-	-	-	-	-	-
Heuchera parviflora	-	-	-	T	T	T	-	-	-	-	-	-	-	T	-	-	-	-	T	-	.8	-	-	-	-	-	-	-	-	T	-	-	-	-	-	-	-	-
Lactuca serriola	T	-	-	-	-	-	T	-	-	T	T	-	T	T	-	T	-	-	T	-	-	T	-	-	-	-	-	T	T	-	-	-	-	T	-	-	T	-	-
Lupinus sp.	-	T	-	3.3	T	.8	-	-	-	-	-	-	T	-	-	T	T	.8	1.7	0.8	.8	-	-	T	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Montia perfoliata	T	-	-	0.8	-	-	T	-	-	T	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Miscellaneous vegetation	-	1.7	5.0	8.3	5.8	10.8	5.8	1.7	6.7	6.7	0.8	10.0	15.0	7.5	10.8	9.2	1.7	14.2	19.2	10.0	20.8	0.8	4.2	10.0	11.7	2.5	12.5	6.7	3.3	16.7	-	-	3.3	3.3	2.5	9.2	2.5	-	10.8
Rock	3.3	2.5	3.3	4.2	2.5	3.3	1.7	0.8	-	-	0.8	-	1.7	10.8	3.3	4.2	1.7	-	15.0	7.5	-	10.0	8.3	3.3	6.7	20.8	6.7	17.5	13.3	8.3	1.7	0.8	-	35.0	29.9	12.5	50.0	46.7	31.7
Bare Ground	12.5	4.2	.8	5.0	2.5	-	24.2	0.8	-	65.8	17.5	-	67.5	10.0	-	13.3	-	-	8.3	10.0	3.3	13.3	-	-	70.8	14.2	6.7	10.0	16.7	-	19.2	7.5	-	14.2	5.0	-	20.8	5.0	-
Litter	4.2	19.2	68.3	67.5	44.0	30.8	-	35.0	48.3	3.3	18.3	41.7	0.8	24.2	29.2	5.0	31.7	52.5	21.7	32.5	37.5	0.8	29.2	45.0	-	19.2	39.2	45.0	32.5	30.0	15.8	36.7	45.0	4.2	21.7	51.7	1.7	15.8	31.7
Moss and lichens	34.2	22.5	4.2	-	12.5	16.7	28.3	14.2	2.5	20.8	36.7	15.8	-	15.0	34.2	23.3	18.3	5.8	20.0	17.5	12.5	32.5	24.2	7.5	-	12.5	15.0	20.0	30.0	25.8	22.5	17.5	22.5	9.2	12.5	10.8	2.5	11.7	10.0

[1] Half of stand 15 was grazed by horses in 1982.

APPENDIX A-2

Canopy cover, percent or mid-point for species present in ravine stands. T = present as small or scattered individual plants. Stands 1, 6, 8, 10, 11, and 12 were not visited in 1980. Stands 10 and 14 were not visited in 1982.



Shrubs

Acer glabrum

Alnus sinuata

Amelanchier alnifolia

Corylus cornuta

Lonicera utahensis

Physocarpus malvaceus

Prunus virginiana

Prunus spp.

Ribes lacustre

Rosa woodsii

Rosa gymnocarpa

Rubus idaeus

Rubus parviflorus

Salix scouleriana

Shepherdia canadensis

Spiraea betulifolia

Symphoricarpos albus

Vaccinium globulare

Seeded grasses

Agropyron trichophorum

Bromus inermis

Dactylis glomerata

Festuca arundinacea

Other herbs

Achillea millefolium

Actaea rubra

Aden[illegible]

Anaphalis margaritacea

Angelica arguta

Artemisia ludoviciana

Aster foliaceus

Aster laetevirens

Astragalus canadensis

Athyrium filix-femina

Bromus ciliatus

Bromus vulgaris

Calamagrostis rubescens

Carex lenticularis

Carex geyeri

Carex sp.

Cerastium arvense

Chrysanthemum leucanthemum

Cirsium arvense

Cirsium scopulorum

Collomia linearis

Delphinium barbeyi

Disporum trachycarpum

Epilobium angustifolium

Equisetum arvense

Festuca idahoensis

Festuca subulata

Fragaria spp.

Frasera speciosa

Galium triflorum

Geranium richardsonii

Geum macrophyllum

Heracleum lanatum

Hieracium spp.

Lathyrus nevadensis

Lupinus argenteus

Mitella pentandra

Osmorhiza chilensis

Pedicularis sp.

Polemonium pulcherrimum

Potentilla gracilis

Prunella vulgaris

Pteridium aquilinum

Ranunculus cymbalaria

Senecio triangularis

Smilacina stellata

Stellaria crispa

Taraxacum officinale

Thalictrum occidentale

Trifolium spp.

Trillium ovatum

Veratrum viride

Viola sempervirens

Miscellaneous vegetation

Moss

Litter

Rock

Bare ground

Apparently [illegible]

Although some individuals showed [illegible] were not [illegible] these species [illegible] were not [illegible] these species [illegible] were not [illegible] these species

Crane, M. F.; Habeck, James R.; Fischer, Willi
in a western Montana Douglas-fir forest. Re
Department of Agriculture Forest S
Experiment Station; 1983. 32 p.

Development of natural vegetation and see
Douglas-fir forest area is described for the
described separately for ravine and upland sit
moss recovery and tree seedling distribution a

KEYWORDS: fire effects, plant
fire, fuels

The Intermountain Station, headquartered in Ogden, Utah, is one of eight regional experiment stations charged with providing scientific knowledge to help resource managers meet human needs and protect forest and range ecosystems.

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Evaluating Nonindustrial Private Landowners for Forestry Assistance Programs: A Logistic Regression Approach

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RESEARCH SUMMARY

As budgets in forest management agencies become more restrictive, cost-effective programs become more important. This paper describes a quantitative tool for setting priorities for the forestry assistance program administered by the Montana Division of Forestry. Logistic regression was used to better identify the type of forest owners to which assistance should be directed. (In logistic regression, the dependent variable is a probability that a certain event or activity will occur.) Data supporting model development were obtained from a questionnaire survey of forest landowners in the western portion of Montana. Four models were developed that pertain to past use of technical assistance, intention to harvest timber, and timber benefits as motivation for forest ownership. The most consistently useful independent variables were geographic region and past timber harvest activity. The author discusses procedures for interpreting results and for rating land ownerships for assistance. One model is discussed in detail, but the discussion is applicable to the other three models. Supporting data are presented for all models.

Evaluating Nonindustrial Private Landowners for Forestry Assistance Programs: A Logistic Regression Approach

Ervin G. Schuster

INTRODUCTION

Public programs providing technical forestry assistance to owners of nonindustrial forest land have become part of the forest economy in the United States. The Private Forestry Assistance (PFA) program administered by State Foresters (formerly known as the Cooperative Forest Management [CFM] program) along with extension forestry within the USDA Cooperative Extension Service, and to a lesser extent the State and Private Forestry division of the USDA Forest Service, provide the bulk of assistance. Assistance is ostensibly aimed at enabling the landowner to make informed decisions to accomplish personal objectives. Although the programs have multiple-use goals, the landowners' objectives usually favor timber growing, harvesting, and marketing. These programs, therefore, affect timber supply.

Recently, renewed interest in small, privately owned timber holdings coupled with static or declining assistance program budgets have compelled a closer look at the processes by which technical assistance is delivered to forest landowners. Increasingly, assistance must be delivered in a more cost-effective manner. Undersecretary of Agriculture John B. Crowell, Jr., recently spoke of the need to "improve the effectiveness of public programs aimed at encouraging more productive management of nonindustrial, private lands" (speech to the Forest Industries Committee on Timber Valuation and Taxation, Scottsdale, Ariz., November 4, 1982). Traditional programs will not meet that challenge.

Assistance programs would be improved if foresters could identify the landowners who will be most responsive to assistance. Better targeting of efforts and the rating of applicants would help. Given an appropriate data base, a logistic regression model is well suited to this need. This paper reports development of such models for western Montana and use by the Montana Division of Forestry, Department of State Lands. Although a few similar efforts can be found in Eastern States (see for examples Jones and Thompson 1981; Trokey 1981), none are known for the Intermountain West. The technique described in this paper, therefore, has the potential for widespread application.

METHODS

During the late 1970's, the Montana Division of Forestry and the USDA Forest Service undertook a cooperative study of the attitudes and activities of private landowners in Montana. A questionnaire was mailed to a stratified random sample drawn from the listing of forest landowners maintained by the Division of Forestry for use in its fire protection program. Responses from owners of less than 40 acres of forest land and from owners in eastern Montana were eliminated from the data base due to sampling problems. The final 41 percent response rate was explicitly analyzed for response bias; no statistically significant bias was found. Results were published in 1978 (Schuster 1978). The 499 completely usable responses from that study constitute the data base of this present study.

The Montana Division of Forestry requested that the Intermountain Forest and Range Experiment Station reanalyze data from the earlier study. The new objective was to develop information and relationships that would enable service foresters to better identify landowners that not only wanted and needed technical assistance, but who would also be likely to use or apply the assistance provided. Unfortunately, the latter question was not addressed in the original questionnaire.

Specific questions in the following categories were selected from that survey as the best indicators of landowner desire for and acceptance of technical assistance:

- Landowner's previous use of forestry assistance, either public assistance or private consultant.
- Landowner's stated intention to harvest timber products in the future.
- Landowner's stated reasons for owning forest land related to production of timber products.

The first category was selected because it obviously and explicitly deals with using technical assistance. The latter two categories were included because of the strong timber and wood products orientation of participants in assistance programs. Although the specific questions were linked to the assistance program, each stands alone and may be used to assess other issues. Responses to selected questions from these areas were used to represent the dependent (Y) variables, the variables to be

predicted in this research. Note that these variables were not modeled to predict behavior of landowners who responded to the original survey. Rather the purpose is to model responses from previous participants as an indication of behavior of other landowners.

The questionnaire also contained information about landowners and their forest holdings that would be useful in predicting the key indicators of landowner response to assistance:

- Ownership-size class.
- Timber-size class.
- Previous timber harvest activity.
- Landowner age.
- Landowner education.
- Landowner income.
- Landowner occupation.
- Geographical location of forest land.

This list represents potential independent (X) variables.

Two analytical techniques are particularly well suited to the type of prediction needed in this research—the discriminant function and the logistic function. The difference can be illustrated with the question: Will a specific landowner use technical forestry assistance? Given measurements on the independent (X) variables reflecting landowner characteristics, the discriminant function will predict an outcome (the Y) as being either yes or no. Given the same set of measurements, the logistic function will predict the numerical probability. For example, given a set of landowner characteristics, the discriminant function might predict an outcome of "no," will not use assistance; whereas the logistic function might predict the outcome as 0.15, a 15 percent probability that assistance will be used. The logistic function, sometimes referred to as a "logit model," was judged more suitable for this study.

The logistic function resembles a typical multiple linear regression function, but also differs from it. Three aspects warrant mention. First, while the multiple regression function is a linear function, the logistic function is nonlinear. Second, in the case of multiple regression, the statistical model is of the form:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_i X_i \qquad (1)$$

The regression coefficients (β's) show the linear relationship between the independent variables (X_i) and the dependent variable (Y). A logistic regression model instead estimates a probability. This is done by means of the ratio of natural logarithms:

$$P(E) = \frac{e^{Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_i X_i}}{1 + e^{Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_i X_i}} \qquad (2)$$

All symbols are as before, except for P(E), the probability of an event, which lies between 0.0 and 1.0; and "e", the base of natural logarithms, which is approximately 2.718. Third, interpretation of the regression coefficients is different. In the case of multiple linear regression, each coefficient (β_i) can be directly interpreted as the effect of a unit change in X_i on Y, when all other variables are held constant. For the logistic model, β_i represents the effect of a unit change in X_i on the exponent of "e". This attribute makes it somewhat more difficult to interpret coefficients. For a more complete discussion of the logistic function, see Pindyck and Rubinfeld (ch. 10, 1981).

Study data were analyzed by means of the Stepwise Logistic Regression feature of BMDP Statistical Software (Dixon 1981). Each dependent variable was transformed to take on only 0 or 1 values. All independent variables were formulated in terms of categories or classes. For example, the variable, landowner age, has three classes, one of which is 65 years and older. All dependent variables together with their class designations are shown later as part of table 2.

Initial model construction involved unrestricted entry and exit of variables until no additional variable could achieve statistical significance, based on the F statistic with $\alpha = 0.10$. Many sets of observations (cases) had "missing" values for one or more independent variables (some respondents did not answer some questions in the original questionnaire). Because the computer program automatically excluded any case with missing values, effective sample size was frequently reduced to about 300. Final model construction involved refitting all data to models containing only the statistically significant variables identified in initial model construction; the stepwise procedure was not used. This increased effective sample size from 300 to between about 350 and 500 cases.

Traditional statistical measures of model goodness, such as R^2, are not very useful to assess logistic regression models. Rather, their overall ability to correctly predict the event being studied, for example as reflected by Chi-square, is a more useful measure. This aspect will be discussed along with other study results.

RESULTS

This study estimated four logistic regression models whose dependent variables had been identified as being important to administration and implementation of the Private Forestry Assistance program in Montana. Estimates for dependent variables should be interpreted as the probability of a landowner behavior event occurring (P[E]). The four landowner events studied pertain to:

- E1. **Using** the services of a Private Forestry Assistance **(PFA)** forester.
- E2. **Using any** technical assistance services, either from a PFA forester or a private forestry consultant.
- E3. **Harvesting** timber from forest land at **any** future time.
- E4. **Currently** owning forest land either for **timber** production (income from the growth and sale of timber or other forest products) or for farm or domestic use (source of forest products for own use—firewood, fenceposts, etc.).

Logistic Models

Although the specific details of the four logistic regression models are different, the form of the results and their interpretation process are identical. Additionally, some models are sufficiently complex so that narrative presentation is too cumbersome. For these reasons, results for only the first (E1) model, using a PFA forester, will be presented. But the discussion also applies to the other models. Data needed to interpret those models will be displayed in tables and figures.

The likelihood of a forest landowner using the services of a PFA forester was found to significantly vary as a function of size of ownership and region of location. The region variable has three class categories: northwest, southwest, and central, as displayed in figure 1. The ownership size variable also has three classes: 40-159 acres (16.2-64.3 ha), 160-639 acres (64.8-258.6 ha), and 640 or more acres (259.0 or more ha). Other factors (tree size, owner age, income, etc.) probably influence use of PFA, but did not increase predictability by a statistically significant amount over ownership size and region.

Overall, only about 18.8 percent of western Montana forest landowners have used the services of a PFA forester, but substantial differences exist between regions and size-classes. Table 1 shows the effect of these differences and the probability of using the PFA program. There is a pronounced regional effect wherein, regardless of size-class, landowners in the southwest region have a higher probability of use than in the northwest and both greatly exceed the central region. Similarly, owners in the middle size-class, independent of region, have the highest probability of use; the smallest size-class has the lowest. Consequently, middle size-class owners from the southwest region have the highest probability of use, while central region owners in the smallest size-class have the lowest use probability.

Table 1.—Probability of Montana forest landowner using services of a PFA forester, by region and size-class

Size-class	Region		
	Northwest	Southwest	Central
Acres			
40-159	0.127	0.150	0.037
160-639	.271	.311	.089
640 +	.264	.303	.086

The probabilities of using the PFA program (E1) are easily displayed. Only two independent variables were statistically significant, each with three classes or categories. Results could be displayed in a 3 X 3 table. But those are the **only** easily displayed results. Table 2 shows all logistic regression models and information pertaining to the statistically significant variables. Rather than presenting a series of complex tables to display results, the process of computing the probabilities shown in table 1 from the data for the equivalent model (E1) in table 2 will be fully explained. Probabilities analogous to those in table 1 could easily be computed for any model, as desired by the reader.

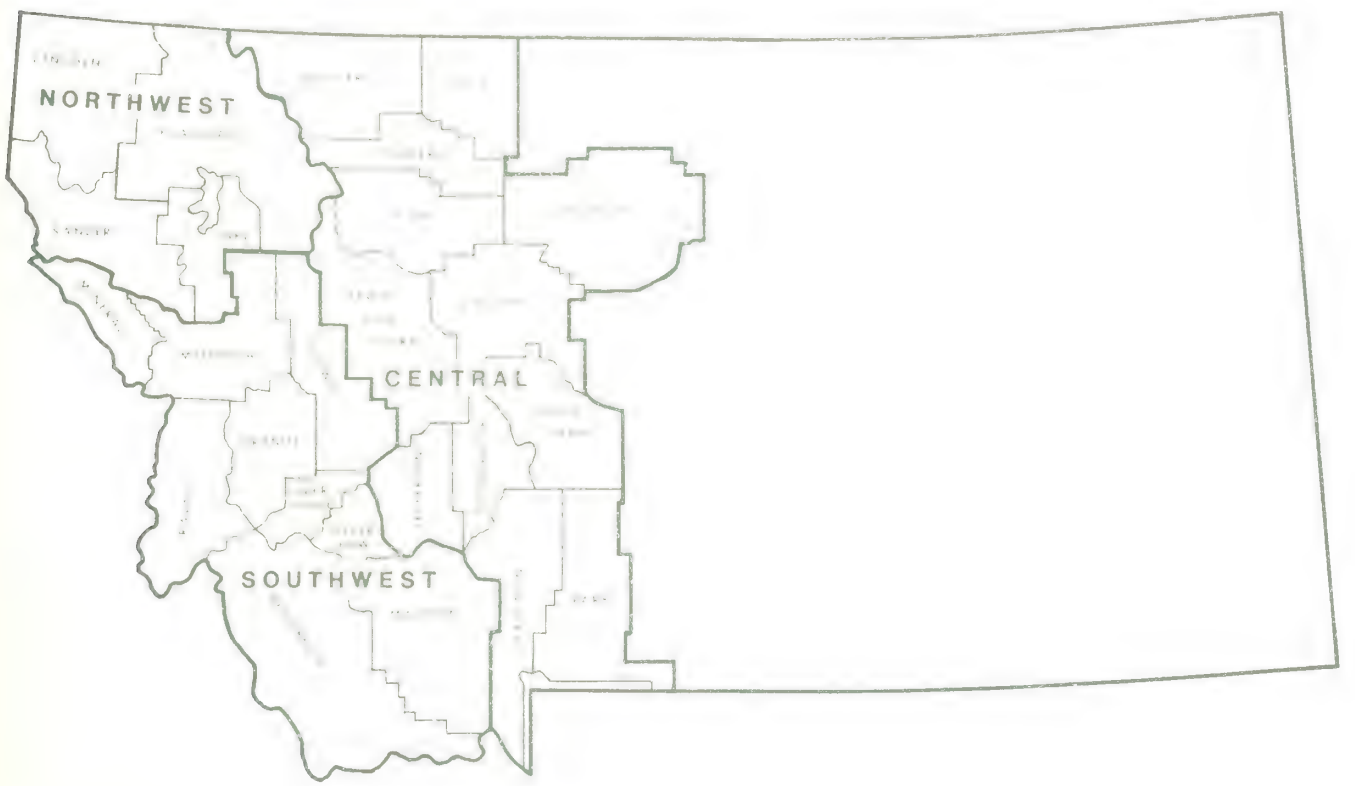

Figure 1.—Three geographical regions within Montana.

Table 2.—Partial exponents for logistic regression models

Variable or factor	Classes or categories	E1	E2	E3	E4
		Using PFA	Using any	Harvest any	Current timber
Constant	—	-1.694	-2.487	1.801	-1.667
Ownership size	40-159 acres	-.614	-.564	-.585	—
	160-639 acres	.326	.259	.338	—
	640 + acres	.288	.305	.247	—
Timber size	≤5 inches	—[1]	—	—	-.002
	5-9 inches	—	—	—	-.316
	≥9 inches	—	—	—	.318
Prior harvest	Yes	—	.552	.859	1.197
	No	—	-.552	-.859	-1.197
Age	44 years and under	—	—	.484	—
	45-64 years	—	—	.446	—
	65 years and older	—	—	-.930	—
Education	1-8 years	—	—	—	-.400
	9-12 years	—	—	—	1.003
	Post-high school	—	—	—	-.646
	Bachelors degree	—	—	—	.701
	Postgraduate	—	—	—	-.659
Occupation	Professional	—	1.790	—	.580
	Administrative	—	.473	—	.232
	Sales	—	.781	—	-1.759
	Crafts	—	1.185	—	-1.021
	Operator	—	.240	—	-.573
	Laborer	—	-8.092	—	.069
	Farmer/Rancher	—	1.404	—	.636
	Retired	—	.936	—	-.261
	Other	—	1.285	—	2.100
Region	Northwest	.380	.465	—	.965
	Southwest	.573	.445	—	-.030
	Central	-.953	-.910	—	-.935

[1]Dashes (—) indicate variable as not statistically significant.

Data contained in table 2 are a condensed form of the logistic regression models, the coefficients and associated design matrixes. They constitute the contribution of each category to the logistic model. Consider the probability of 0.311 shown in table 1 for southwest region owners in the 160-639-acre (64.8-258.6-ha) size-class. Refer now to the data in table 2 for the appropriate variable category pertaining to the E1—Using PFA model:

Constant..... (-1.694)
Size—160-639 acres ..... (0.326)
(64.8-25.8.6 ha)
Region—southwest ..... (0.573)

The numbers (-1.694, 0.326, and 0.573) are used to quantify $\hat{Y}$ in equation 2:

$$P(E1) = \frac{e^{\hat{Y}}}{1 + e^{\hat{Y}}}$$

Simply determine $\hat{Y}$ as the sum:

$$\hat{Y} = -1.694 + 0.326 + 0.573$$
$$= -0.795$$

Hence:

$$P(E1) = \frac{e^{-0.795}}{1 + e^{-0.795}}$$
$$= 0.311 = 31.1 \text{ percent}$$

Similarly, to estimate the probability of using PFA by central region owners in the smallest size-class:

$$P(E1) = \frac{e^{\hat{Y}} \quad \hat{Y} = -1.694 + (-0.614) + (-0.953) = -3.26}{1 + e^{\hat{Y}} \quad \hat{Y} = -3.26}$$
$$= 0.037 = 3.7 \text{ percent}$$

Probabilities for other events, E2-E4, are determined by using the procedure just described. It is important that each significant variable have a coefficient in the summation.

For some purposes, it may not be necessary to calculate probabilities with great precision. An approximation will be sufficient. Table 3 provides a listing of $\hat{Y}$ values together with the associated probability of event values. Consider the case of 160-639-acre (64.8-258.6-ha) owners in the southwest region where $\hat{Y} = -0.795$. Inspection of table 3 shows -0.8 to be the closest $\hat{Y}$ value; its associate P(E) is 0.310 which corresponds to 0.311 shown above. Since all probability values can be calculated exactly, use of table 3 is optional.

Table 3.—Probability of events for corresponding values of $\hat{Y}$

$\hat{Y}$	P(E)
10.0	0.000
8.0	.000
6.0	.003
5.5	.004
5.0	.007
4.5	.011
4.0	.018
3.5	.029
3.0	.047
2.5	.076
2.0	.119
1.8	.142
1.6	.168
1.4	.198
1.2	.232
1.0	.269
0.8	.310
0.6	.354
0.4	.401
0.2	.450
0.0	.500
0.2	.550
0.4	.599
0.6	.646
0.8	.690
1.0	.731
1.2	.769
1.4	.802
1.6	.832
1.8	.858
2.0	.881
2.5	.924
3.0	.953
3.5	.971
4.0	.982

Data contained in table 2 can also be used less analytically. The numbers themselves indicate relative importance in determining the probability of an event occurring. The bigger the number, the larger the effect on probability. Consider the E1 model. The smallest numbers in table 2 are associated with the 40-159-acre (16.2-64.3-ha) size-class and the central region. Both have relatively large negative values (-0.614 and -0.953 respectively). Table 1 shows these categories have lower probabilities and when combined constitute the lowest probability. Conversely, the highest probabilities in table 1 are for the middle size-class and the southwest region, variable categories with the largest values in table 2. Table 2 values should be compared within a column, not between columns. Table 2 values contribute to the size of the exponent ($\hat{Y}$); therefore effect on probability is not proportional to size.

The quality of a logistic regression model is determined by its ability to predict outcomes correctly. Moreover, the goodness of predicted probabilities can be verified only in the context of a large number of prediction opportunities. Although the probabilities can be applied to a specific forest landowner, evaluation of the probabilities estimated by logistic regression is best done by reference to the combined outcomes over many individuals. Table 4 compares predicted and actual percentages of landowners using the PFA program, both derived from the study data base.

Table 4.—Actual and predicted participation (percentage) in PFA programs by size-class and region

Participation				Sample
Actual	Predicted	Size-class	Region	size
Percent		*Acres*		
5.7	3.7	40 - 159	Central	35
6.9	6.3	160 - 639	Central	31
8.8	8.6	640 +	Central	34
12.2	12.7	40 - 159	Northwest	90
14.6	15.0	40 - 159	Southwest	82
26.8	27.1	160 - 639	Northwest	82
27.9	26.4	640 +	Northwest	43
28.6	30.3	640 +	Southwest	42
33.3	31.1	160 - 639	Southwest	45

Consider the case of northwest region landowners in the 40-159 acre (16.2-64.3 ha) size-class. The logistic regression model predicted that 12.7 percent of the 90 landowners would use the PFA program. In fact, 11 of the 90, amounting to 12.2 percent, of the landowners did. Comparisons between predicted and observed participation for the other logistic regressions, E2-E4, are very similar to those shown for E1, but are too complicated to present here. The E1 logistic regression model yielded the best predictions; the E2 model the worst predictions, based on a Chi-square analysis.

Cut-off Points

Although the overall accuracy of the logistic regression models are revealed in the context of a large number of landowners, their application in forestry assistance is to set priorities for the assistance program. A rule or cut-off point must be established by which a class of landowner (or classes) is judged a likely (good) or unlikely (bad) prospective client for the assistance program. One must establish a probability level (P[E]) above which an associated class of landowner (or classes) is judge to be "likely" clients, below which judged "unlikely." In reality the cut-off point would be used as a guideline, a "screening" device to separate the likely from the unlikely prospects. The PFA forester can then focus time and attention on the likely prospects, deemphasizing or screening out the unlikely.

Unfortunately, although individual landowners within a class have similar characteristics (region and ownership size), they do not always behave alike. Any cut-off point will result in errors. A trade-off exists between correctly identifying those landowners for which an event (using PFA services) will occur and correctly identifying those for which the event will not occur. (This problem is analogous to the statistical problem of a Type I and

Type II error.) Figure 2 graphically depicts these trade-offs for each of the four logistic models being presented. Shown in the frame pertaining to the E1 model, a lower cut-off point (say P(E1) = 0.05) will correctly identify all individuals that did use PFA forester services (coded "Using PFA"). But it fails miserably at identifying those that did not (coded "Not Using"). If the cut-off point were set at P(E1) = 0.05, then any class of landowners where the associated P(E1) were greater than 5 percent would be judged as likely clients. The cut-off point would correctly identify about 95 percent of the users, but only about 10 percent of the nonusers. That

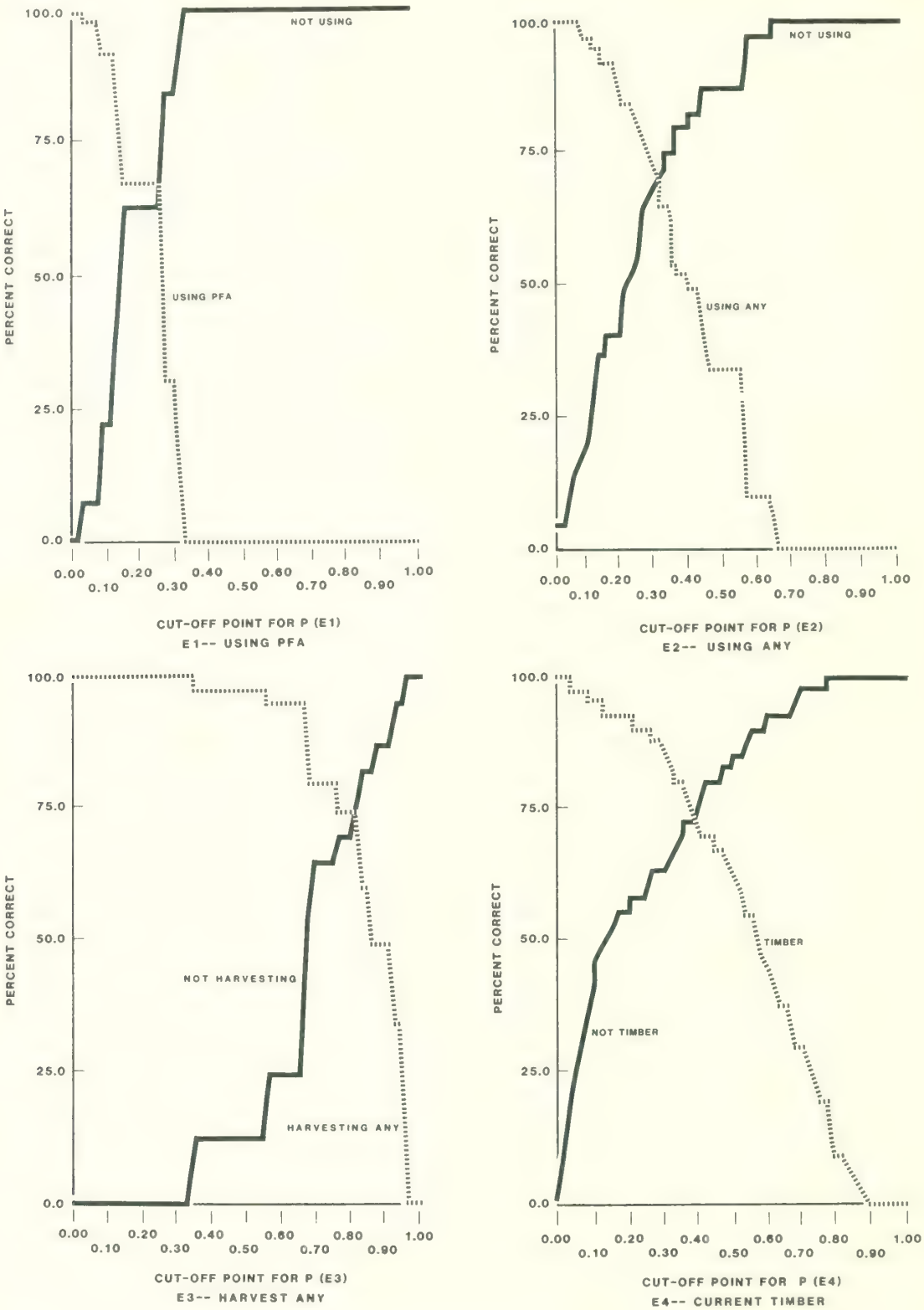

Figure 2.—Cut-off point analyses for logistic regressions

is, about 90 percent of the nonusers would be mistakenly identified as users.

The low cut-off level screens nobody and leads to the conclusion that virtually everyone will use PFA services. On the other hand, a high cut-off level leads to the conclusion that nobody will use the services of a PFA forester. Figure 2 shows that if the cut-off level were set anywhere between a probability value (P[E1]) of 15 to 25 percent, about 67 percent of the users and about 62 percent of the nonusers would be correctly identified. Below that level users would be better identified, but many nonusers would be misidentified as likely users. Conversely, above that level, likely users would increasingly be misidentified as likely nonusers.

Cut-off points must be decided for all logistic regressions (E1-E4) presented in this paper. The probability level selected should relate to the consequences (or costs) of misidentification. For example, if it is very important to correctly identify all likely PFA program users and it is not particularly costly to identify nonusers as users, a low cut-off point is appropriate. Alternatively, if the capability to provide assistance is limited such that correct identification of unlikely clients is critical, a relatively high cut-off point is appropriate. The four frames of figure 2 provide the information for determining cut-off points for all (E1-E4) logistic regression models.

DISCUSSION AND APPLICATIONS

This paper presents results from logistic regression models pertaining to landowner use of the forestry assistance program provided by the Montana Division of Forestry, Department of State Lands. Unfortunately, the available data base did not exactly address that topic. Several surrogate models were developed, each of which only partially related to desired topic. A reasonably simple model, E1—Using PFA, was used to illustrate how questionnaire-type data can be easily converted to probability estimates. The interpretive approach shown for that model should be applied to the other models, as dictated by the user needs. Additionally, users such as the Montana Division of Forestry will have to evaluate these results and develop guidelines for application. Questions must be addressed. For example: Which model or models (E1-E4) should be emphasized and what cut-off points are appropriate?

Assume, for example, that a judgment is made to use the E1—Using PFA as the primary model and E4—Current Timber as the secondary model. Further assume such shortage of funds that it is more critical to screen-out unlikely clients than to correctly identify all likely clients. A relatively high cut-off point would be appropriate. If figure 2 were used to set the cut-off point at 0.28, about 85 percent of the unlikely clients (nonusers) would be screened, but only about 30 percent of the likely clients (users) would be identified. That a higher percentage of likely clients was not identified might be judged acceptable under circumstance of an extreme funding shortage. Table 1 shows that only southwest region landowners in the two largest size-classes meet that standard.

If further restrictions are needed, the E4—Current Timber model could be used analytically, as was the E1 model, or nonanalytically. Inspection of the E4 portion of table 2 for the largest exponents, shows that landowners that have harvested timber, that have 9 to 12 years of education, and that have an "other" occupation will have a relatively high probability of owning forest land for timber production.

The procedure described offers a system for establishing the top priority landowner group wherein assistance would be targeted. Subsequent analysis could be used to develop a more comprehensive priority listing, as needed. The technique described in this report is not highly refined, but it does illustrate the application of logistic regression to the problem. If the general approach is deemed useful, the data base could readily be improved.

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Four logistic regression models were developed from questionnaire data obtained from forest landowners. The models were designed to assist the Montana Division of Forestry to rate clients for the forestry assistance program. Interpreting and applying results is discussed. Basic data are presented.

KEYWORDS: forestry assistance, forest landowners, logistic regression, logit analysis

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Revegetating Processed Oil Shale in the Upper Mountainbrush Zone of Colorado

Robert B. Ferguson
Neil C. Frischknecht

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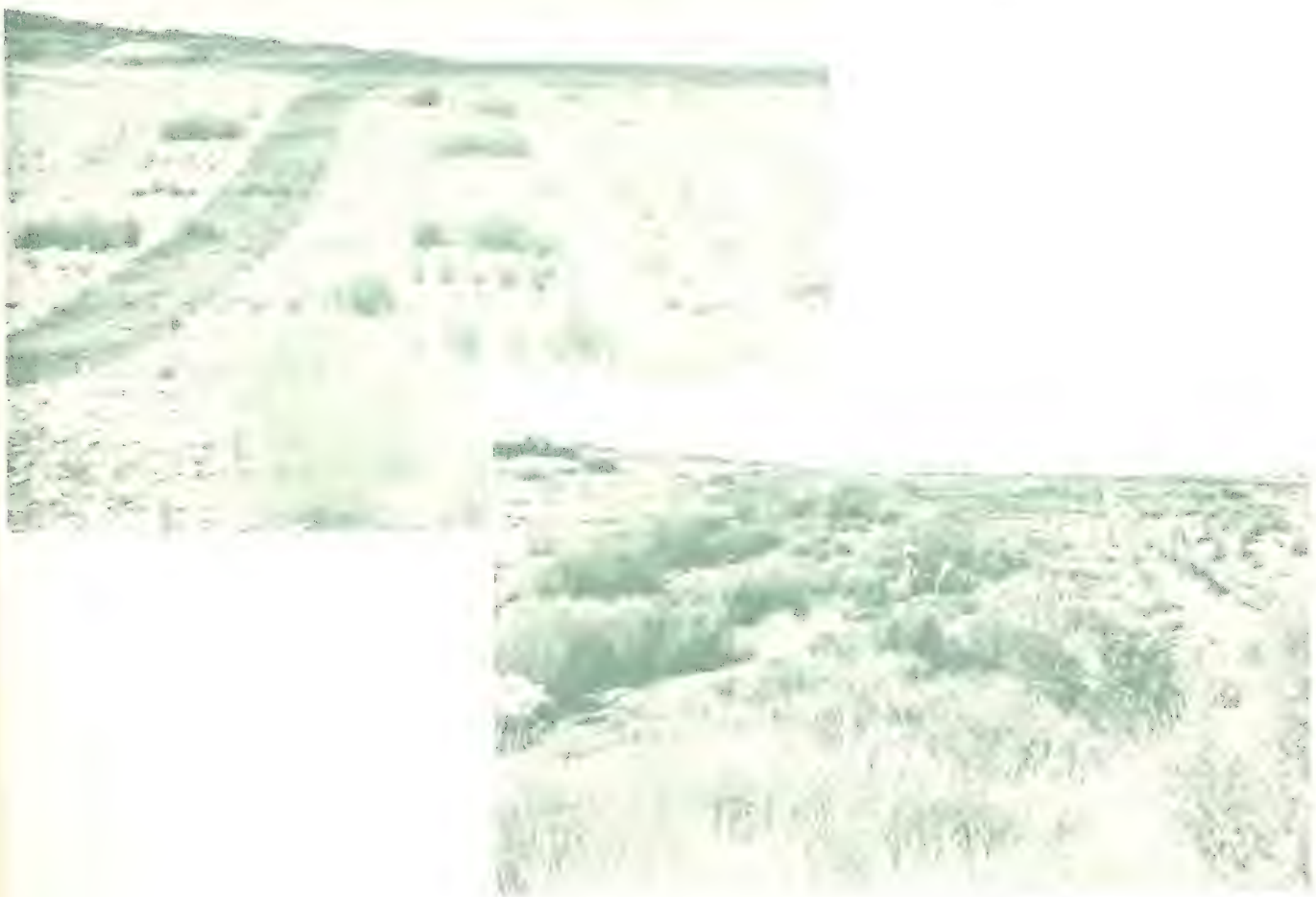

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RESEARCH SUMMARY

This study was designed to provide information on methods to establish vegetation on processed oil shale disposal areas without using large volumes of water to leach salts from the processed shale. A secondary objective was to evaluate several species of plants for their adaptability to the soil material and climatic conditions at the study site.

The study was conducted in Garfield County, Colo., at an elevation of 8,160 ft (2 487 m). Unleached, TOSCO II processed oil shale was amended in three ways: (1) covered with 6 to 10 inches (15 to 25 cm) of topsoil, (2) covered with 2 to 4 inches (5 to 10 cm) of rock fragments, and (3) incorporated with barley straw to a depth of 6 to 8 inches (15 to 20 cm) at the rate of 2 tons per acre (0.73 metric tons per ha). Container-grown transplants of all species of shrubs and one forb species were planted on each soil material in 1976. In addition to the amended, processed shale treatments, the test plants were also planted on subsoil material, which served as a comparison. The study site was shaped to provide a comparison of north, south, and level exposures.

Six years after planting, overall plant survival was four times greater on topsoil-covered processed oil shale than on straw-amended processed shale, and one and a half times greater on topsoil-covered shale than on rock-mulched processed shale. Survival of test plants was affected only slightly by differences in plot exposure, but when survival and growth rate were considered together, the north-facing plots were shown to be most favorable to plants. Only two plant species, fourwing saltbush and prostrate summer cypress, grew equally well on all soil materials. These two, plus rubber rabbitbrush, mountain big sagebrush, and green ephedra, were the only plant species showing satisfactory adaptability on topsoil-covered processed oil shale.

Precipitation received at the study site has been sufficient to gradually decrease the salinity and sodicity of processed oil shale covered by 6 to 10 inches (15 to 25 cm) of topsoil. Maximum temperatures occurring in the top 1 inch (2.5 cm) of processed oil shale may be inimical to seed germination and seedling survival. Otherwise, the temperature regimes and soil water potentials in processed shale should not preclude the successful establishment of adapted plants on uncovered materials.

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Revegetating Processed Oil Shale in the Upper Mountainbrush Zone of Colorado

Robert B. Ferguson
Neil C. Frischknecht

INTRODUCTION

Oil shales of the Green River Formation of Colorado, Utah, and Wyoming have received appreciable attention as a possible source of fuels and chemicals. The Green River Formation underlies some 34,000 mi² (700 000 km²), and the deposits of oil shale in this area constitute the largest source of contained shale oil in the world (Sladek 1974).

The properties of processed oil shale depend greatly on the particular technology used in retorting, and to a lesser extent on the shale mineralogy. Unleached processed oil shale resulting from the TOSCO II process of retorting is a difficult medium on which to establish vegetation. Processed shale has a texture similar to silt loam, a moderate water infiltration rate unless compacted excessively, and a pH within the range suitable for growth of most plants (Berg 1973a). However, it has adverse characteristics such as high salinity and alkalinity, low availability of nitrogen and phosphorus, and a questionable availability of potassium (Schmehl and McCaslin 1973). In addition, it is susceptible to wind and water erosion, and tends to coat low-growing vegetation with fine, black dust.

Berg (1973b) found that a variety of plant species can be established in TOSCO II processed oil shale when considerable quantities of water are used to leach out the soluble salts that are harmful to plant growth. In his study, an estimated 47 to 60 inches (118 to 150 cm) of water were applied during 16 months following seeding.

However, circumstances do not always make such a heavy application of water desirable or practical. Therefore, reclamation planners need to determine if there are plant species that could be successfully established on unleached processed oil shale disposal areas, either with or without the addition of amendments or soil cover.

Schaal (1973a) reported that sawdust and peat amendments to processed oil shale produced limited improvement in plant growth in the greenhouse. He also reported (1973b) that leached processed shale provided an excellent medium for plant growth when plots were mulched with peat and sawdust, and fertilizer was applied. In a field experiment with direct seeding, Merkel (1973) observed very little plant survival on unleached processed shale, mixed success on a 50/50 mixture of soil and unleached processed shale, and excellent survival and growth on native topsoil. Merkel also reported some success with several species of shrubs transplanted into a 3- to 8-inch (7.6- to 20-cm) layer of TOSCO II processed shale spread over topsoil. However, his observations were based on only the first 11 months following transplanting.

This paper presents the results of a study begun in 1976 in cooperation with TOSCO (The Oil Shale Company). TOSCO was formerly a partner in the Colony Shale Oil Project located near Parachute, Colo.

Research objectives were (1) to evaluate the effects of three different amendment treatments applied to TOSCO II processed oil shale on the establishment of planted shrubs and forbs, (2) to compare the establishment of the same species of plants when planted on native subsoil material and on amended processed oil shale, (3) to evaluate differences among species of plants used with respect to adaptability to different growing media and topographic exposures, and (4) to compare air and soil temperatures to which plants are exposed when growing in processed oil shale and in soil.

METHODS

Study Location

The study site is in Garfield County, Colo., at the head of Davis Gulch, a tributary of Parachute Creek, 14 mi (22.5 km) north-northwest of the town of Parachute (formerly Grand Valley). Elevation of the site is 8,160 ft (2 487 m). The mean annual precipitation for this portion of the Roan Plateau is approximately 20 inches (50.8 cm). Annual snowfall will vary from 80 to 100 inches (203 to 254 cm). Snowpack depths of 6 ft (1.2 m) may be expected. June is the driest month and August (as a result of thunderstorms) usually the wettest. More precipitation is received during January through March than for any month except August. Summer temperature maximum is near 95° F (35° C), and winter minimum is near -20° F (-29° C). Mean annual temperature is approximately 41° F (5° C).

A variety of plant communities exist along the Roan Plateau and its slopes (Ferchau 1973), as can be seen in figure 1. In the immediate vicinity of the study site, the vegetation is dominated by a mixture of shrub species including *Artemisia tridentata* subsp. *vaseyana* (Rydb.), *Artemisia frigida* Wild., *Symphoricarpos oreophilus* A. Gray, *Purshia tridentata* (Pursh) DC, *Amelanchier utahensis* Koehne, *Chrysothamnus nauseosus* (Pall.) Britt. subsp. *salicifolius* (Rydb.) H. and C., and

Figure 1.—Roan Plateau, upper portion of Davis Gulch. Aspen community occupies northfacing slope facing the camera. Mountainbrush community covers south-facing slopes and ridges.

Chrysothamnus viscidiflorus (Hook.) Nutt. Common herbaceous plants are *Stipa comata* Trin. & Rupr., *Oryzopsis hymenoides* (R.&S.) Ricker, *Penstemon strictus* Benth., *Eriogonum umbellatum* Torr., and *Machaeranthera bigelovii* A. Gray (Greene). On north-facing slopes, *Populus tremuloides* Michx. forms open to dense stands.

Soils in the vicinity of the study area are Typic Cryoborolls, formed under low temperatures, with a dark surface layer. They are loamy, fine loamy, mixed, and include shallow soils. Local soils are derived from the sandstones, shales, and marls of the Evacuation Creek member of the Green River formation (Fox and others 1973). They are primarily residual, shallow, sandy loams, classified as Lithosols because depth to bedrock averages 9 to 12 inches (23 to 30 cm). The sandstones and shales from which these soils have developed are noncalcareous.

Plot Design

Prior to this study, Colony Development Operation had opened a small basin, approximately 75 by 120 ft (23 by 37 m), for research that failed to materialize. The company had stockpiled about 400 tons (363 metric tons) of TOSCO II processed oil shale at the site on the south edge of the plateau, overlooking Davis Gulch. The small basin was reshaped so that the long axis (120 ft) ran north and south. The reshaped basin provided three equal-sized sections; a south-facing slope of 25 percent, a level section, and a north-facing slope of 25 percent.

Processed oil shale was spread in a band 33 ft (10 m) wide by 120 ft (37 m) long, to a depth of 2.5 ft (0.76 m). The processed shale was compacted only to the extent achieved by operating a rubber-tired front-end loader in the process of spreading and grading. The graded band of processed oil shale was then treated in three ways: (1) covered with 6 to 10 inches (15 to 25 cm) of topsoil taken from the area adjacent to the basin, (2) mulched with a 2- to 4-inch (5- to 10-cm) layer of broken rock fragments from sandstone bedrock in the basin, and (3) amended with barley straw rototilled into the top 5 to 6 inches (15 to 20 cm) of processed shale at the rate of 2 tons per acre (0.73 metric tons per ha). Each treatment occupied a strip approximately 10 ft (3 m) wide by 120 ft (37 m) long. A similar sized strip of rocky subsoil material, also obtained during reshaping of the basin, was placed adjacent to the three strips of treated processed shale. Figure 2 shows the treatment strips.

Figure 2.—Davis Gulch study site in second growing season. Treatments (left to right): subsoil, straw-amended shale, rock-mulch-covered shale, and topsoil-covered shale.

The four treatments were each divided into 30 plots 10 ft (3 m) long by 4 ft (1.2 m) wide. Within each treatment 10 plots faced south, 10 plots occupied the level bottom of the basin, and 10 plots faced north.

Planting of Test Species

On June 11, 1976, nine of the 10 plots of each treatment were planted to a single plant species, 10 plants to a plot. Two species were planted on the tenth plot (five of each) due to a shortage of transplants of those particular species. All plants used were container-grown, and were approximately 1 year old. Six of the species were grown at the Forest Service nursery at Coeur d'Alene, Idaho. The remaining five species were grown in the greenhouse at Provo, Utah.

During summer 1976, rodents (attracted to the plots by seed in the barley straw) destroyed some of the test plants. Replantings were made on September 8, 1976, and June 7, 1977, and a rodent-proof fence was put around the plots in September 1976. Table 1 lists the plant species used as well as information available on the original source of each species.

Plants were each given 0.53 gal (2 l) of water at the time of planting, and approximately 0.26 gal (1 l) on June 23 and July 25 of the first growing season.

Table 1.—Plant species used at the Davis Gulch study area, Garfield County, Colo.

Scientific name	Common name		Source
	Original plantings		
Amelanchier utahensis	[illegible]	U7-67	Enterprise, Utah
Atriplex canescens	Fourwing saltbush	—	Bliss, Idaho
Caragana arborescens	Siberian peashrub	—	Plumfield Nursery, Neb
Chrysothamnus nauseosus	Rubber rabbitbrush	—	Sanpete County, Utah
Cercocarpus montanus	True mountain mahogany	B1-72	Owyhee County, Idaho
Ephedra viridis	Green ephedra	U1-73	Sanpete County, Utah
Hedysarum borealis	Utah sweetvetch	—	Utah County, Utah
Kochia prostrata	Prostrate summer cypress	P.I. 356817	Kazakh, U.S.S.R.
		P.I. 356826	
Lonicera tatarica	Tatarian honeysuckle	—	Plumfield Nursery, Neb.
Sambucus cerulea	Blueberry elder	U18-71	Carbon County, Utah
Symphoricarpos oreophilus	Snowberry	—	Kaiparowits Plateau, Utah
	Replacement plantings (when different from above)		
Artemisia tridentata vaseyana	Mountain big sagebrush	—	San[illegible]nty, Utah
Atriplex canescens	[illegible]	—	[illegible] Co., Utah
Kochia prostrata villosissima	[illegible]cypress	P.I. 343101	[illegible]
Sambucus racemosa	Red elder	—	[illegible]nknown

Container-grown plants of mountain big sagebrush were planted on June 8, 1977, as replacements for true mountain mahogany, none of which survived through the first winter.

Data on plant survival and growth (height and mean diameter) were recorded in September and October 1976; May, July, and September 1977; June, July, and September 1978; July and October 1979; Augus[illegible] and August 1981.

Microclimatic Data and Soil Sampling

A solar-powered, battery-operated data logging s[illegible] was installed at the Davis Gulch study area in August 1977. Thermistor sensors and thermocouple psychrometers for measuring air and soil temperatures and soil water potentials, respectively, were installed on both north and south slopes (25 percent) on plots located 30 yd (27 m) to the west of the shrub plantings. On each slope a 30- by 30-ft (9-m by 9-m) area was cleared of all vegetation and divided in half. In the center of each half, a 35.3-ft^3 (1-m^3) block of soil was excavated and replaced with either TOSCO II processed oil shale or local topsoil. Thermistors and thermocouple psychrometers were placed at several depths as the pits were refilled. Processed oil shale or soil was spread over the remainder of the 15- by 15-ft (4.5- by 4.5-m) area to a depth of 4 inches (10 cm). The data logger was programed to record data from all sensors, including a tipping bucket rain-gage, at hourly intervals.

Beginning in the autumn of 1978, processed oil shale and soil cores were obtained with a 3.25-in (8.2-cm) diameter soil auger from each aspect of each treatment on the planted area, for salinity and sodicity analyses.

RESULTS

Effect of Treatment and Slope Aspect

Six growing seasons after planting, overall mean survival of plants was highest on subsoil plots (table 2). Mean survival on topsoil-covered processed shale plots was four times greater than on straw-amended processed shale plots, and 50 percent greater than on rock-mulched processed shale plots. Mean height of each species after 6 years is shown in table 3.

Throughout the study, there was little difference in overall plant survival on different exposures. After six seasons, mean survival on the north, level, and south exposures was 41, 38, and 37 percent, respectively. However, the values shown in table 4 help put the overall effect of exposure in perspective. When the number of surviving plants on each exposure is multiplied by the mean height of all plants on that exposure, a success index is obtained for each treatment-exposure combination. As might be expected, the values in table 4 suggest that the north exposure was the most favorable environment for plants in terms of combined survival and growth. Although the overall mean height of surviving plants shown in table 3 would seem to indicate little difference in plant growth on the different soil materials, the similar overall mean height after 6 years is due primarily to the similar growth rate of fourwing saltbush and prostrate summer cypress. Also, the mean height of several other species on the straw-amended and rock-mulched shale plots was increased because of a number of plants that grew within 1 ft (30 cm) of either the topsoil-covered shale or the subsoil plots. Most likely the roots of these latter plants extended into the adjacent topsoil or subsoil.

Table 2.—Percent survival of 11 plant species after six growing seasons, by type of soil material, Davis Gulch, Colo., 1981

Species	Processed shale			Subsoil
	Topsoil-covered	Rock-mulched	Straw-amended	
Fourwing saltbush	97	94	64	77
Siberian peashrub	70	80	26	100
Prostrate summer cypress	78	79	33	35
Rubber rabbitbrush	81	54	11	80
Mountain big sagebrush	31	17	7	57
Tatarian honeysuckle	80	12	0	85
Green ephedra	17	23	0	78
Utah sweetvetch	29	9	3	93
Blueberry and red elder	69	7	4	41
Utah serviceberry	20	0	0	np*
Mountain snowberry	43	20	0	13
Mean	56	36	13	66

*np = not planted.

Table 3.—Mean height of 11 plant species after six growing seasons, by type of soil material, Davis Gulch, Colo., 1981

Species	Processed shale			Subsoil
	Topsoil-covered	Rock-mulched	Straw-amended	
	Inches (cm)			
Fourwing saltbush	54 (137)	52 (132)	54 (137)	55 (140)
Siberian peashrub	18 (46)	9 (23)	6 (15)	34 (86)
Prostrate summer cypress	30 (76)	31 (79)	34 (86)	29 (74)
Rubber rabbitbrush	18 (46)	14 (36)	22 (56)	29 (74)
Mountain big sagebrush	21 (53)	12 (30)	20 (51)	25 (64)
Tatarian honeysuckle	16 (41)	14 (36)	—	23 (58)
Green ephedra	14 (36)	14 (36)	—	15 (38)
Utah sweetvetch	6 (15)	6 (15)	7 (18)	11 (28)
Blueberry and red elder	21 (53)	10 (25)	23 (58)	53 (135)
Utah serviceberry	9 (23)	—	—	—
Mountain snowberry	11 (28)	10 (25)	—	12 (30)
Mean	20 (50)	17 (44)	24 (60)	29 (73)

Table 4.—Index of shrub height × survival by treatment and aspect of exposure, Davis Gulch, Colo.

Treatment	Plot aspect			Total
	North	Level	South	
Subsoil	[1]1912	1777	1833	5522
Topsoil-covered shale	1584	1300	1385	4269
Rock-mulched shale	1012	815	941	2768
Straw-amended shale	793	408	892	2093
Total	5301	4300	5051	

[1]Index calculated by multiplying the number of surviving shrubs on each aspect by the mean height of all surviving shrubs on that aspect.

The relatively poor showing of the level exposure in this comparison may have been the result of poor drainage of soil water. The basin used to obtain both north and south exposures resulted in some ponding of surface runoff and snowmelt on portions of the level bottom of the basin.

Species Adaptability

Tables 2 and 3 show the percent survival and mean height of 11 of the plant species. The 12th species, true-mountain mahogany, failed to survive past the first season. If judged by their ability to survive and exhibit at least minimal growth on subsoil, all of the test species except the accession of snowberry from the Kaiparowits Plateau are adapted to the climate of the Roan Plateau. A local ecotype of snowberry may be found that is more adapted to conditions of the study area. Most promising, from the standpoint of both survival and growth after six growing seasons, are fourwing saltbush, prostrate summer cypress, rubber rabbitbrush, mountain big sagebrush, and green ephedra. Although percent survival of sagebrush and ephedra was low on the topsoil-covered shale plots, the surviving plants exhibit good growth and appearance.

Siberian peashrub, elderberry, Tatarian honeysuckle, and Utah sweetvetch cannot be recommended for reclamation use if no more than 6 to 10 inches (15 to 25 cm) of topsoil is used to cover processed oil shale. The first three of these species exhibited good survival on topsoil-covered shale, but growth was poor. Utah sweetvetch might be expected to grow reasonably well if the depth of topsoil were several inches deeper than it was in this study.

Fourwing saltbush and prostrate summer cypress grow as well on topsoil-covered processed shale as on subsoil, which is a good indication of their tolerance to saline soil material. In fact, these two species exhibited excellent growth on all plots, including the straw-amended shale plots (figs. 2 and 3).

Most of the prostrate summer cypress planted on the study plots were from the original Soil Conservation Service plant introduction numbers 356817 and 356826. However, those used as replacement stock were from SCS P.I. No. 343101 (subsp. *villosissima*). The former two accessions reached somewhat greater size than did the villous subspecies, and may provide greater ground cover and forage.

New plants of both prostrate summer cypress and fourwing saltbush have become established from seed on the plot area. Prostrate summer cypress has also been successful in spreading onto rocky, bare areas adjacent to the study plots, with some new plants growing 20 ft (5 m) away from parent plants. Seedlings of the villous subspecies of prostrate summer cypress appeared to outnumber those of the other two accessions on the straw-amended processed shale plots, perhaps indicating that in the seedling stage the villous variety is more salt tolerant than the other accessions.

Of the five most successful species, only sagebrush and rabbitbrush are native along the upper reaches of the Roan Plateau, where the study was conducted. Local ecotypes of big sagebrush and rubber rabbitbrush may

Figure 3.—Davis Gulch study site, August of sixth growing season. Largest plants are fourwing saltbush, prostrate summer cypress, and blueberry elder.

[illegible]en more successful than those used in this study, which were from Sanpete County, Utah.

Utah sweetvetch, Siberian peashrub, Tatarian honeysuckle, and blueberry elder have all produced seed, but no new plants have resulted to date. Tatarian honeysuckle has suffered some winter dieback. Siberian peashrub was clipped by rabbits on several occasions during winter, which retarded the growth of this sp[illegible] because deep snow nearly always makes the upper portions of plants available to foraging animals. Utah sweetvetch was clipped by rabbits during the summer.

Tatarian honeysuckle, mountain snowberry, Siberian peashrub, and serviceberry all suffered some loss or damage as a result of pocket gophers feeding on the roots.

A number of native plant species have invaded the study plots since they were established in 1976. Thirty-one species were identified on topsoil-covered plots, 22 on subsoil plots, 18 on rock-mulched plots, and 4 on straw-amended plots. Among the invading plant species were four shrubs: *Artemisia frigida* Willd., *A. tridentata* subsp. *vaseyana* (Rydb.), *Chrysothamnus nauseosus* (Pall.) Britt. subsp. *salicifolius* (Rydb.), and *Chrysothamnus viscidiflorus* (Hook.) Nutt. *A. frigida* and *C. viscidiflorus* successfully invaded all treatments except the straw-amended shale. *A. tridentata* has so far been found only on the topsoil-covered shale plots and subsoil plots. *C. nauseosus* has become established on only the topsoil-covered shale plots. The much larger number of native species invading the rock-mulched and topsoiled plots supports the advisability of covering processed oil shale with a layer of soil material.

Many of the herbaceous species invading the topsoiled plots have exhibited excellent vigor and produced abundant seed. Among these are *Oryzopsis hymenoides* (R.&S.) Ricker, *Hordeum jubatum* L., *Phacelia hastata* Doug. ex Lehm., *Penstemon strictus* Benth., *Penstemon*

pachyphyllus Gray, *Achillea millefolium* L., *Eriogonum umbellatum* Torr., and *Astragalus spatulatus* Sheld.

Kilkelly and Lindsay (1982) noted that the high boron (B) content of TOSCO II processed oil shale might be inimical to the growth of some plant species. In their studies, they observed sparse vegetative cover on plots of TOSCO II retorted shale without soil cover, and individual plants were stunted in size, with scorched leaves, compared with plants growing on soil control plots. Although we did not determine the B content of any of the plant species growing on our study plots, the possibility exists that B toxicity was a factor in the poor survival of many species, especially on that part of the study area where the processed shale was not covered by topsoil. Conversely, after 6 years the surviving plants of prostrate summer cypress and fourwing saltbush growing on straw-amended processed shale appeared as vigorous as those growing on topsoil-covered processed shale.

Temperature and Water Potential of Processed Shale

The environment encountered by plants on a processed oil shale disposal area will vary according to the microclimate of each disposal site. Growing conditions will be different at 8,000 ft (2 400 m) in the mountain-brush zone from those at 5,000 ft (1 500 m) in the salt desert shrub zone.

At Davis Gulch, as well as on plots at Sand Wash in Utah, a characteristic of processed oil shale was observed that may explain the differences in temperature measured at various depths in processed shale and in soil. As the warm, dry season of the year begins, moisture stored in processed shale evaporates at an increasing rate. As evaporation proceeds, salts are moved to the surface, and the surface layer of about 1 to 1.5 inches (2.5 to 4 cm) becomes porous, with a thick, often whitish, crust. Unless a hard rain breaks down this porous surface layer it probably acts as a barrier to heat transfer and moisture evaporation. Thus, the temperature regime in processed oil shale at various seasons of the year depends partly on whether or not this porous surface layer is present and how long it persists.

On the south-facing slope at Davis Gulch, temperatures of processed shale and soil at the ¾-inch (2-cm) depth differed between the 2 years in which data were obtained. In 1978 mean temperatures were higher in processed shale than in soil during the first half of June. For the remainder of that summer, mean temperatures were higher in soil than in processed shale (table 5) except on days when rainfall occurred. In 1980, mean temperatures at the ¾-inch depth were higher in processed shale than in soil from the beginning of measurements on April 11 to the last date of observation on October 6 (table 6).

Table 5.—Mean monthly temperatures (°C) of both bare processed oil shale and bare topsoil at five depths on a south exposure with a 25 percent slope, and of the air at a height of 54 inches, Davis Gulch, Colo., 1978

Measurement	Temperature, °C						
	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Air 54 inches	15.7	19.4	16.6	12.1	6.8	-2.0	-10.9
Topsoil ¾ inch	19.9	24.3	21.7	16.6	10.8	1.4	-3.1
Processed shale ¾ inch	20.3	23.0	20.8	16.0	10.6	1.3	-3.8
Topsoil 4 inches	17.7	22.1	20.2	16.0	10.9	1.9	-2.4
Processed shale 4 inches	19.0	22.4	20.5	16.2	11.3	2.2	-3.4
Topsoil 8 inches	16.6	21.1	19.7	16.0	11.4	3.0	-1.5
Processed shale 8 inches	18.2	22.2	21.0	16.9	12.2	3.4	-2.3
Topsoil 16 inches	15.1	19.7	19.1	16.0	12.0	4.5	-0.2
Processed shale 16 inches	16.6	21.2	20.9	17.6	13.3	5.3	-0.7
Topsoil 32 inches	12.0	16.4	17.1	15.3	12.4	6.8	2.2
Processed shale 32 inches	13.1	17.7	18.8	17.0	13.8	8.1	2.3

Table 6.—Mean [illegible] of both bar[illegible]ed oil [illegible] 54 in-

Measurement	[illegible]	Temperature, C May	June	July[2]	Aug.	Sept.[3]
Air 54 inches	2[illegible]	9.3	17.7	19.1	17.4	10.2
Topsoil ¼ inch	[illegible]	[illegible]	19.4	19.9	19.1	18.1
Processed shale [illegible]	[illegible]	10.2	22.2	24.1	21.9	18.5
Topsoil 4 [illegible]	[illegible]	[illegible]	17.6	20.0	18.7	17.4
Processed [illegible] 4 inches	[illegible]	9.1	20.1	23.1	21.3	17.0
[illegible]	[illegible]	[illegible]	[illegible]	19.0	18.8	16.6
8 inches	[illegible]	[illegible]	18.7	22.2	21.0	16.9
Topsoil 16 inches	[illegible]	[illegible]	13.9	17.8	18.2	15.9
Proces[illegible]	[illegible]	[illegible]	16.9	21.0	20.6	[illegible]
Topsoil 32 inches	[illegible]	[illegible]	11.0	15.1	16.3	14.6
Pr[illegible] [illegible]	[illegible]	[illegible]	12.7	17.3	18.6	16.0

[illegible]

Mean maximum temperatures [illegible] processed [illegible] were 70° C [illegible] and [illegible] F 42° C, and 41° C) for the months of May, June, and July 1980, respectively, on the south-facing slope. Corresponding mean maximum temperatures in soil were 61 [illegible] F [illegible] and 87 [illegible] On the north-facing slope, mean maximum temperatures for the [illegible] were [illegible] F, [illegible] and 35° C) in processed shale and 59 [illegible] F, [illegible] and 84° F (15° C, 28° C, and 29 [illegible] C) in soil.

Daily maximum temperatures at the 4-inch depth were mild during May, but in June and July temperatures [illegible] C) were common. Processed oil shale temperatures near the surface were not lowered as much as soil temperatures by rainfall, although the effects of wetting could depend on whether rains come as showers followed by sunshine the same day, or whether rain is accompanied by overcast skies lasting most, or all, of the day.

Mean temperatures of processed oil shale were nearly always higher than mean temperatures of soil at all depths from 4 to 32 inches (10 to 80 cm) from June through November (tables 5 and 6). From December into March, mean temperatures of processed shale were about 1.8° F (1° C) less than mean temperatures of soil.

On the north aspect plots at Davis Gulch, temperature regimes of processed oil shale and soil were generally related to one another in the same manner as on the south aspect. However, differences between processed shale and soil tended to be less because the effects of incoming solar radiation were moderated by the north-facing plots.

The effect of snow cover in moderating temperature regimes in both processed shale and soil was apparent. As the winter progressed, snow depths became deeper on the north aspect than on the south aspect, and [illegible] materials decreased faster on the south-facing slope than on the north-facing slope. On the south slope, frost penetration reached the 32-inch [illegible] m) depth by December 31, and both soil and pro[illegible]d shale were still frozen at this depth on March 15. On the north slope, frost reached the 32-inch depth only in the processed shale by December 31, and then for only 3 days.

[illegible] temperatures 2 inches (5 cm) above the surface were occasionally higher over processed shale than over soil on both south and north aspects, but seldom by more than 3.6 [illegible] F (2° C).

The assessment of the relative soil water potential regimes in the bare processed oil shale and bare soil was hampered by our being unable to visit the study plots frequently. From June 15 through October 31, 1978, psychrometer readings were taken on eight occasions. For the eight readings, soil water potential on the south-facing soil plot averaged -13, -6, and -11 bars at the 8-, 12-, and 20-inch (20.3-, 30.5-, and 50.8-cm) depths, respectively. Soil water potential on the south-facing processed shale plot averaged -19, -9, and -10 bars at the same

depths. On the north-facing soil plots, average soil water potential for the eight readings was -15, -15, and -10 bars at the 8-, 12-, and 20-inch depths, respectively. On north-facing processed shale plots, comparable averages were -15, -12, and -12 bars. Thus, on southerly slopes the soil water potential in the top 1 ft (30 cm) of processed oil shale may usually be slightly lower than that in soil during much of the growing season. On northerly slopes there may be little difference between processed shale and soil with respect to water potential.

Conversely, the limited number of readings taken during the summers of 1979 and 1980 indicated that processed oil shale may, at times, exhibit higher soil water potentials than soil, on both north and south slopes.

Salinity of the Growing Medium

Topsoil and processed oil shale samples collected in the third through sixth growing seasons indicate that salinity and sodicity of both materials had decreased on topsoil-covered plots (table 7). The amount of salts in the soil material profile may vary with the season of the year; decreasing during periods of increasing soil moisture, and increasing again as the soil profile dries and capillary action brings dissolved salts upward in the profile. In this study, samples were taken in late summer or early autumn and should be representative of near maximum values of salinity and sodicity for each year.

Sufficient precipitation fell at the study site to prevent any increase in soil salinity by capillary rise of soil water with the passage of time. Although no adequate record of precipitation amounts was obtained, annual precipitation at the four nearest official weather stations was relatively normal for the 1976 through 1981 period except for being lower than normal in 1977 and higher than normal in 1981. Precipitation along the crest of the Roan Plateau should be about 20 inches (50.8 cm) annually, with at least half the total received during the snow-free period. The apparent gradual decrease in sodicity will be beneficial to plants established on soil-covered processed oil shale.

The electrical conductivity and sodium adsorption ratio of processed shale beneath a 2- to 4-inch (5- to 10-cm) layer of slowly decomposing rock mulch remained essentially the same through the first five growing seasons, but decreased sharply in 1981, due possibly to the much greater than normal rainfall received during summer 1981. The electrical conductivity of processed shale that was amended with straw decreased throughout the study period, whereas the sodium adsorption ratio changed little until the sixth year (1981) when it showed a large decrease.

CONCLUSIONS

We drew the following principal conclusions from our study:

1. Fourwing saltbush and prostrate summer cypress flourished under all treatments, and can be unequivocally recommended for use in the reclamation of processed oil shale disposal areas.

2. Covering unleached TOSCO II processed oil shale with 8 to 10 inches (20 to 25 cm) of topsoil resulted in reasonably good initial establishment of 11 of the 12 plant species tested. However, when survival and rate of growth is considered, only five of the 12 species can be recommended for use on the crest of the Roan Plateau: fourwing saltbush, prostrate summer cypress, rubber rabbitbrush, mountain big sagebrush, and green ephedra. Other tested species showed lower survival and growth rate after 6 years when grown on processed oil shale covered with 6 to 10 inches (15 to 25 cm) of topsoil.

3. Although both the villous and nonvillous forms of prostrate summer cypress established and grew well in the environment encountered in this study, the villous (grey) form was more aggressive in terms of reproduction, especially on the most saline areas.

4. The successful invasion by a number of native perennial species of grasses and forbs on topsoil-covered, unleached, processed oil shale indicates that 8 to 10 inches (20 to 25 cm) of topsoil covering may be adequate for herbaceous species having shallower root systems than most shrubs. Therefore, at least 1 ft (30 cm) of topsoil covering is recommended for herbaceous species.

5. The amount of precipitation received along the crest of the Roan Plateau of western Colorado appears sufficient to prevent salts in unleached, processed oil shale from migrating upward into a topsoil covering. Rather, a gradual decrease in salinity and sodicity of processed oil shale covered by topsoil may be expected.

Table 7.—Change in sodium adsorption ratio (SAR) and electrical conductivity (EC_e, mmhos/cm) of the saturation extract of soil materials on the Davis Gulch study plots

Soil materials	Third season		Fourth season		Fifth season		Sixth season	
	SAR	EC_e	SAR	EC_e	SAR	EC_e	SAR	EC_e
Topsoil (above shale)	1.5	1.8	0.6	1.3	0.4	0.6	0.7	0.5
Shale (beneath topsoil)	2.7	8.2	.8	8.5	.9	3.1	.6	3.3
Rock-mulched shale	12.7	23.0	11.0	27.0	17.0	25.0	6.2	7.8
Straw-amended shale	16.6	31.0	11.0	22.0	16.0	18.0	2.8	5.7

No evidence was indicated of a need for a capillary barrier between processed oil shale and a topsoil covering as advocated by Redente and Cook (1981) for sites at lower elevations in the Piceance Basin.

6. Maximum temperatures in the surface 1 inch (2.5 cm) of unshaded, processed oil shale are significantly higher than maximum temperatures in unshaded topsoil on south-facing slopes. During June and July, maximum temperatures of 104° F to 122° F (40° C to 50° C) in processed shale on south slopes could inhibit or prevent germination of seed of some plant species, and might also be lethal to very young seedlings. At depths below the surface inch, the temperature regime in processed shale was not sufficiently different from that in topsoil to adversely affect plant growth.

7. On the south-facing slope, soil water potentials were only slightly lower in the upper 1 ft (30 cm) of unleached, TOSCO II, processed oil shale than in the upper foot of topsoil. On the north-facing slope, soil water potentials during the growing season were very similar in processed shale and topsoil.

RECOMMENDATIONS

1. Cover processed oil shale with a minimum of 8 inches (20 cm), and preferably 1 ft (30 cm), of topsoil prior to attempting revegetation. If this can be done, it should not be necessary to leach the processed oil shale following its placement at the disposal site.

2. The use of a capillary barrier between Tosco II processed oil shale and a soil covering is not deemed necessary at disposal sites along the crest of the Roan Plateau.

3. For rapid soil protection, utilize fourwing saltbush and prostrate summer cypress, even though they are not native plant species on the upper Roan Plateau.

4. Include local ecotypes of rubber rabbitbrush and big sagebrush in any revegetation program for processed oil shale disposal areas where a minimum of 8 inches (20 cm) of topsoil can be placed over the processed shale. Also give serious consideration to using the nearest source of green ephedra on topsoiled processed shale, especially if the revegetation is planned for elevations between 6,000 and 7,000 ft (1 830 and 2 140 m).

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Ferguson, Robert B.; Frischknecht, Neil C. Revegetating processed oil shale in the upper mountainbrush zone of Colorado. Res. Pap. INT-321. Ogden, Utah: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 9 p.

TOSCO II processed oil shale was covered with topsoil or rock mulch, or amended with straw. Establishment and growth of planted, container-grown shrubs, and changes in salinity of processed shale and soil were monitored for 6 years. Temperatures in processed oil shale and soil are compared.

KEYWORDS: processed oil shale, revegetation, topsoiling, species adaptability, Colorado, capillary barrier, soil temperature, soil amendment, *Kochia prostrata, Atriplex canescens*

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Measuring Species Diversity on Revegetated Surface Mines: An Evaluation of Techniques

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RESEARCH SUMMARY

This report reviews the three most commonly used techniques for measuring species diversity in plant communities: (1) diversity indices, (2) rank correlation tests, and (3) similarity indices. The author discusses the suitability of each technique for assessing species diversity on mined land and evaluates the most often used indices, test statistics, or coefficients of each technique. Applications of the Shannon-Weiner diversity index, Spearman's rank order correlation coefficient, Motyka and others' and Bray and Curtis' version of Sorensen's similarity index, and Spatz' version of Jaccard's index for assessing mined land species diversity are presented in the appendix.

Several constraints render diversity indices inappropriate for the assessment of mined land species diversity. They do not provide direct comparisons between two communities, nor do they distinguish differences in the species-specific apportionment of individuals among species (evenness). Rank correlation tests provide only a relative comparison of species or life form apportionment and do not directly evaluate differences in species or life form numbers or identities. Similarity coefficients provide direct comparisons of both richness and evenness and appear to be well-suited for evaluating mined land diversity.

Measuring Species Diversity on Revegetated Surface Mines: An Evaluation of Techniques

Jeanne C. Chambers

INTRODUCTION

The Surface Mining Control and Reclamation Act of 1977 requires establishment of "a diverse, effective, and permanent vegetative cover . . . capable of self-regeneration and plant succession" (PL 95-87.91 STAT 491, para. 19). Currently, species diversity must be evaluated on revegetated coal mined lands prior to bond release. Developing methods for assessing species diversity has proven difficult, primarily because technical and conceptual information is lacking.

The concept of species diversity and its relationship to mined lands must be understood before methods of measurement can be discussed. Species diversity is most often equated with Whittaker's (1972) definition of alpha diversity: the within-habitat or intracommunity diversity. Alpha diversity includes both species number (richness) and the manner in which importance is proportioned among species (evenness). The importance of a species is a measure of the species' biological activity and of the amount of the community's resources that the species uses (Whittaker 1972); it is usually derived from estimates of numbers (density), production, and cover. Because alpha diversity is a more precise term than species diversity, it will be used throughout this paper.

Mined land diversity has frequently been assessed simply as species richness. The justification for the use of species richness is exemplified by Peet's (1974) statement that "Direct species counts, while lacking theoretical elegance, provide one of the simplest, most practical, and most objective measures of species richness." Peet also stated that species counts convey no useful information about underlying community relationships. Two communities that have the same numbers of species can exhibit very different relationships of species importances. Peet (1974) suggested that comparing species richness between communities may be invalid unless it is assumed that the contributions of individual species to community functioning are similar. This assumption is seldom met in a comparison of a revegetated area to a reference area, or a premining community.

Intuitively, the ideal measure of alpha diversity would combine both species richness and species evenness. Although the two-component approach appears well-suited to the evaluation of alpha diversity it is not a flawless method; Pielou stated that:

> It is futile to debate whether the loss in information that results from combining (or "confounding") these two properties is offset by the gain in simplicity resulting from use of a single index. Obviously there is no answer to this question; it must always depend on the reason for which diversity indices and measures of evenness were calculated in the first place, that is, on the nature of the underlying ecological problem whatever it may be.

Numerous measures of alpha diversity that combine both richness and evenness have been devised, but many are not applicable for evaluating revegetated mined lands. Because the standard used to assess the alpha diversity of revegetated mined land is usually the premining community or a reference area, measures selected for the evaluation must be suitable for direct comparisons between two communities. The selection of an appropriate diversity measure or measures is crucial in obtaining a valid assessment of alpha diversity.

Measurements of alpha diversity can be placed into three general categories: (1) diversity indices, (2) rank correlation tests, and (3) similarity indices. Each of the three will be reviewed and the applicability of each measure to the assessment of mined land alpha diversity will be discussed. Appendixes I, II, and III give sample calculations of the most frequently used index of each of the three types of measurements. Because the choice of an importance measure can greatly affect the final value of the index, appendix IV discusses the selection of importance measures.

DIVERSITY INDICES

Diversity indices are by far the most frequently used measures of alpha diversity. They can be subdivided into two major categories: dominance indices and information theory indices. Although numerous diversity indices exist, the most commonly used are variations of four basic indices: Simpson's index, McIntosh's index, Shannon-Weiner's index, and Brillouin's index. Each of the four will be reviewed and then the assumptions and constraints associated with the entire group will be discussed.

Simpson's and McIntosh's Indices

Simpson's index is a dominance index that measures the probability that two individuals selected at random from a sample will belong to the same species (Simpson 1949). In its simplest form, the calculation for an infinite sample is:

$$\text{Simpson } \lambda = \sum_{i=1}^{s} p_i^2$$

where p_i is the proportion of the individuals in species i. Because this formulation varies inversely with alpha diversity, Greenburg (1956) and Berger and Parker (1970) have suggested subtracting the Simpson index from its maximum possible value of one. Therefore, the inverse or the complement value of the formulation above is usually used as a diversity index.

Figure 1 shows the response curve for this index. Indices of this type are termed dominance indices because divergence of species importance values consistently results in an increase in the index value (Peet 1974). This means that the index emphasizes the more common species in the community.

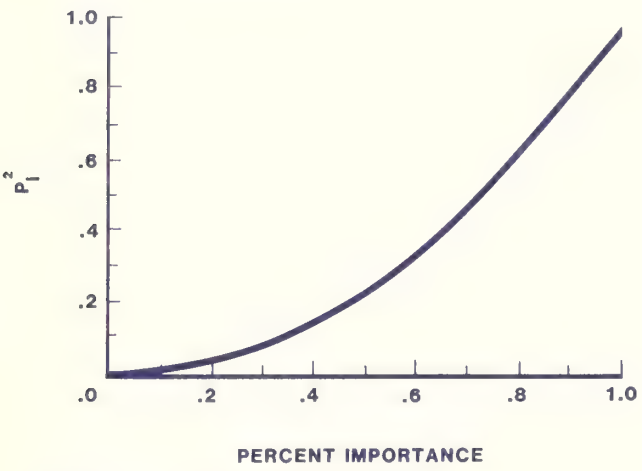

Figure 1.—The response curve of a dominance index represented by the Simpson index (from Peet 1974).

McIntosh (1967) has proposed a dominance index similar to that of Simpson's based upon a distance measure of the ecological similarity between samples. A stand can be thought of as a point in an n-dimensional hyperspace where each dimension refers to the abundance of a particular species. The similarity between stands is determined by the magnitude of the calculated distance values. The value for a single point in the n-dimensional hyperspace is defined as:

$$\sqrt{\sum_{i=1}^{s} n_i^2}$$

where n = the number of individuals of a single species and s is the number of species. The index in its final form expresses the observed diversity as a proportion of the absolute maximum diversity for a given sample size (N):

$$\text{McIntosh } N = \frac{\sqrt{\sum_{i=1}^{s} n_i^2}}{N - \sqrt{N}}$$

If percentage importance is to be used instead of numbers of individuals, the index becomes:

$$\text{McIntosh } 1 - \sqrt{(\sum_{i=1}^{s} p_i^2)}$$

This index then has the same properties of dominance as Simpson's index.

The Shannon-Weiner and Brillouin Indices

Both the Shannon-Weiner index and the Brillouin index are referred to as information theory indices (Peet 1974). Pielou (1966) has explained the connection of information theory with the measurement of species diversity, stating that alpha diversity ". . . means the degree of uncertainty attached to the specific identity of any randomly selected individual. The greater the number of species and the more nearly equal their proportions, the greater the uncertainty and hence the diversity." She suggested that because information content is a measure of uncertainty, it is a valid measure of diversity.

The Shannon-Weiner index gives the information content per individual within an infinite population:

$$\text{Shannon-Weiner } H' = -\sum_{i=1}^{s} p_i \log p_i$$

where p_i is the percentage importance. A finite population can be described using the Brillouin formula:

$$\text{Brillouin } H = \frac{1}{N} \log \frac{N!}{N_1!\, N_2! \ldots N_s!}$$

where N is the total number of individuals, s the number of species, and N_i the number of individuals in the ith species. The base of the logarithm used determines the units in which diversity is measured, but does not alter the results.

The response curve shown in figure 2 illustrates that the Shannon-Weiner index is most sensitive to changes in those species that exhibit a relative importance of about 20 to 50 percent. The majority of the information theory indices, including the Brillouin index, exhibit this type of response curve.

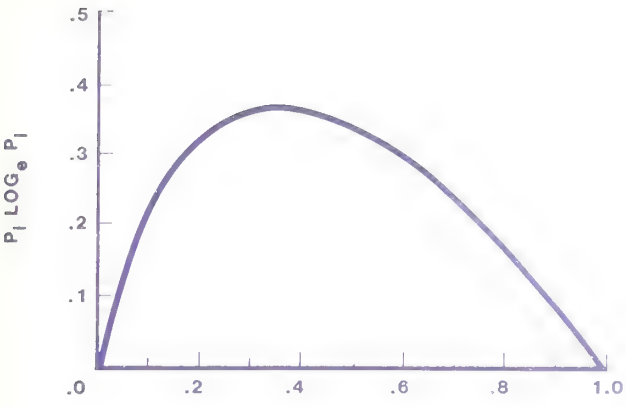

Figure 2.—The response curve of an importance index, represented by the Shannon-Weiner index (from Peet 1974).

Evaluation

Diversity indices, in general, are currently very popular measures of diversity and have often been assumed to provide "absolute" measures of diversity regardless of the type of importance value used or the kinds of communities investigated. Certain of the properties inherent in diversity indices, however, appear to render them inappropriate for the evaluation of mined land diversity. For example:

1. In general, diversity indices were devised for use with numbers of individuals and assume that all individuals are equal to one another (Pielou 1974). This is obviously not the case when dealing with such varied life forms as trees and grasses or forbs and shrubs and in practice, importance values are often substituted for numbers of individuals.

2. Diversity indices are statistically comparable only if based upon numbers of individuals (Lyons 1981; Pielou 1966) and even then, their comparability is questionable. Pielou (1966) suggests an estimate of variance based upon the usual sample variances of adjusted differences between values of H obtained from independent subsamples. A statistical technique proposed by Lyons (1981) uses importance values to assign a fixed weight to every individual of a species. Neither method has been validated.

3. It is difficult to compare values obtained from two different communities using certain diversity indices because a change in the index at one end of the scale is not necessarily proportionate to the same amount of change at the other end (see the response curves in figs. 1 and 2). Thus, index values obtained from different communities are not directly comparable, and individual index values cannot be reapportioned to 100 percent as suggested by Bonham and Larsen (1980) for the Shannon-Weiner index.

4. When examining two different communities, diversity indices do not reveal changes in the apportionment of individuals among species or in the identity of species (Peet 1974). For example, a reference area might have species A, B, C, D, and the apportionment of individuals might be 10, 2, 2, 1, respectively. If the revegetated area had the same species, A, B, C, D, but the apportionment of individuals was reversed, 1, 2, 2, 10, the diversity indices would still be the same for both areas. A completely different set of four species on the reclaimed area with the same set of apportionment values would also yield an identical index, although the reclaimed community would definitely be "different" than the reference community.

5. All diversity indices that contain a term for species number are said to be relativized. They are sample-size-dependent and two populations are comparable by these measures only when the sample sizes are identical (Peet 1975).

The value of diversity indices in assessing vegetation on surface mines has been mentioned (Wali 1980; Sindelar 1980), but concrete results have not been published. The State of Colorado at one time required certain mining companies to determine the diversity of reclaimed mined lands with the Shannon-Weiner index (Crofts 1981). In addition, Bonham and Larsen (1980) recommended that the Shannon-Weiner index be used to assess mined land diversity on all reclaimed mined lands administered by Region IV of the Office of Surface Mining (OSM). Given the constraints and assumptions previously listed, use of the Shannon-Weiner index as a sole criterion of diversity is not warranted. It is particularly inappropriate because it cannot describe the specific apportionment of importance among species between two areas, such as a revegetated and a reference area.

RANK CORRELATION TESTS

A direct, statistical measure of the values reflecting species importance (production, cover, or density) between reference and revegetated areas would appear to be a logical method for assessing diversity. Spearman's rank correlation coefficient provides a nonparametric statistical measure of the similarity between the two areas, as reflected by the relative importance of the various species or life forms within the two areas. The coefficient is based on the differences between the rank of each of the species or life forms that exist in the two areas; where the ranks are given the values of 1 for the most abundant species; 2 for the second most abundant species, etc. A rank correlation coefficient of 0 would suggest complete independence between the rankings of the two areas (no correspondence between the species that are most abundant in the revegetated area). A coefficient of 1 would indicate a perfect correspondence.

Spearman's rank order correlation coefficient is one of several such coefficients based on ranks. Its computation is explained in many statistics texts (Sokal and Rohlf 1969; Snedecor and Cochran 1967). Spearman's Rho, as this coefficient is sometimes called, assigns greater weights to those species or life form pairs that demonstrate large differences, than do some other rank correlation coefficients (Kentall's Tau). A test to determine whether Rho is greater than 0 is presented in appendix II.

The use of rank correlation tests for assessing mined land diversity is limited because of the following constraints:

1. Rank correlation tests provide only a relative comparison of species or life form apportionment, because ranking values are used instead of actual importance measures.

2. Tests of independence between two different areas do not directly evaluate differences in species or life form numbers or identities. Although provisions can be made for unequal numbers of species or life forms through "tie-breaking" procedures, large differences in species or life form composition between the two areas greatly decreases the validity of the test.

SIMILARITY INDICES

Similarity indices provide mathematical expressions for the similarity of communities (Mueller-Dombois and Ellenberg 1974). Such indices have been variously referred to as community coefficients and overlap indices. Historically, similarity indices have been used for the ordination of plant communities. Depending upon the type of index, the inputs are in the form of binary presence-absence data or importance values (often relativized). Similarity coefficients are scaled from 0 or -1 (no overlap in the distributions of observations among categories) to 1 (identical distributions). Dissimilarity coefficients are scaled from 0 to 1 or infinity, with 0 as maximum similarity. Because similarity indices can provide a simple mathematical comparison of the richness or richness and evenness (heterogeneity) of two communities, such as a revegetated and reference community, they seem particularly promising for the evaluation of mined land diversity.

Like diversity indices, similarity indices can be divided into several different classes: (1) those that require only an enumeration of the different resource states or presence-absence data, (2) indices that are based upon distance measurements, (3) indices that utilize information theory, and (4) indices derived from probability functions. The most commonly used indices in each class will be reviewed and recent comparisons of individual indices will be discussed.

Indices that Use Presence-Absence Data

The simplest indices are those that require only presence-absence data. They are, in general, a function of the number of plant species or life forms found in both communities as well as the number found in only one community or the other. Romesburg (personal communication) and Marshall and Romesburg (1979) described most commonly used indices and explained their application. Janson and Vegelius (1981) examined 20 indices of this type using 6 different criteria to determine the value of each index for measuring the degree of coexistence between two species over different localities. They concluded that only three indices, Ochiai's coefficient, r_o (1957), Dice's coefficient, r_d (1945), and Jaccard's coefficient, r_j (1908), met all six of their criteria. The formulas for these three indices are as follows:

$$\text{Ochiai } R_o = \frac{A}{\sqrt{A + B} \cdot \sqrt{A + C}}$$

$$\text{Dice } R_d = \frac{2 \cdot A}{2 \cdot A + B + C}$$

$$\text{Jaccard } R_j = \frac{A}{A + B + C}$$

When two species, s_1 and s_2, are being compared, A = the occurrence of both species, B = the occurrence of species s_1, and C = the occurrence of species s_2. These three indices are of value for the assessment of species diversity on mined lands only if a comparison of species numbers or richness is desired.

Indices that Include Importance Values

Similarity indices not included in Janson and Vegelius' (1980) study that incorporate the importance value of each species or life form are Motyka and others' (1950) and Bray and Curtis' (1957) version of Sorensen's index and Spatz' (1970) version of Jaccard's index. Bray and Curtis' version of Sorensen's similarity index is merely a computational simplification of Motyka and others' version that requires the use of percentage values for each species or life forms. Because these indices allow a direct comparison of two communities and are combined measures of richness and evenness, they may apply to the assessment of alpha diversity on mined lands.

Motyka's version of Sorensen's similarity index (IS_{mo}) is:

$$IS_{mo} = \frac{2\,MW}{MA + MB} \times 100$$

where MW = the sum of the smaller importance values of the species or life forms common to both areas, MA = the sum of the importance values of all species or life forms in one area, and MB = the sum of the importance values of all species or life forms in a second area.

Bray and Curtis' version of Sorensen's similarity index is as follows:

$$IS_{BC} = \frac{2MW}{200} \times 100 \text{ or } IS_{BC} = MW(\text{percent})$$

where MW = the sum of the smaller importance values of the species or life forms common to both areas.

Spatz' modification of Jaccard's index is slightly different than the two previous indices:

$$IS_{SP} = R \times \frac{MC}{MA + MB + MC} \times 100$$

where R = the smaller values of the species or life forms common to both areas divided by the greater values; the fractions are summed and the sum is divided by the total number of species in both areas. MC = the sum of the values of all species or life forms common to both areas, MA = the sum of the values of all species or life forms in one area, and MB = the sum of the values of all species or life forms in the second area. This index consists of two separate parts. The first part (R) expresses the relative similarity of the two areas being compared in terms of the number of common species

and the differences in importance values between individual species. The second part, the quantitative application of Jaccard's index examines the relative similarity of the two areas in terms of importance values.

The index value for each of these indices ranges from 0 to 1 with 1 being complete similarity. A comparison of the calculation of the three indices is presented in appendix III.

Indices Derived from Distance Measurements, Information Theory, and Probability Functions

The other types of similarity indices have recently been compared by Linton and others (1981) and Ricklefs and Lau (1980). Examples of the most frequently used indices of each type will be given and comparisons of the relative merits of each as described in the above studies will be discussed.

Two frequently used distance measurements are the Euclidean distance and Schoener's index (Schoener 1968). The formula for the two indices are:

$$\text{Euclidean distance } D = \left[\sum_{i=1}^{n} \right]$$

$$\text{Average Euclidean distance } D = \frac{\sum}{n}$$

$$\text{Schoener } R = 1 -$$

where p = importance values from measurements of populations j and k in category i. This terminology will be applied throughout the remainder of the discussion.

Horn (1966) devised a similarity index based upon information theory:

$$\text{Horn } R_{\log} = \sum (p_{ij} + p_{ik}) \log (p_{ij} + p_{ik}) - \sum p_{ij} \log p_{ij} - \sum p_{ik} \log p_{ik}$$

Indices based upon probability functions include those of Morisita (1959) and Pianka (1973).

$$\text{Morisita } R = \frac{\sum\sum p_{ij} p_{ik}}{\sum p_{ij}^2 + \sum p_{ik}^2} \quad \text{(modified by Horn 1966)}$$

$$\text{Pianka } R = \frac{\sum p_{ij} p_{ik}}{\sum p_{ij}^2 \sum p_{ik}^2}$$

Ricklefs and Lau (1980) compared Morisita's and Horn's indices and the Euclidean distance, Linton and others (1981) evaluated differences in Schoener's, Horn's, Pianka's, and Morisita's (as modified by Horn 1966) indices. The results of these comparisons were:

1. For all indices, estimates of overlap increased with sample size. Linton and others (1981) found that estimated overlap leveled out at about 16 observations per population.

2. Pianka's and Horn's modification of Morisita's index produced identical results (Linton and others 1981).

3. Linton and others (1981) showed that only Schoener's index estimated overlap correctly when real overlap was between 7 and 85 percent. Similarly, Ricklefs and Lau (1980) found the standard deviations of samples of indices they tested to be greatest when expected overlap was intermediate between 0 and 1.

4. All four indices examined by Linton and others (1981) had similar accuracy with overlaps between 85 to 90 percent, but at higher overlaps, Schoener's index was least accurate.

5. When overlaps were below 7 percent, Schoener's and Horn's indices performed erratically and Morisita's and Pianka's indices were 70 percent below the actual overlap (Linton and others 1981).

In general, similarity indices based upon distance measurements, information theory, and probability measurements are most accurate at intermediate levels of overlap or similarity and are inconsistent at either high or low levels of overlap. Because the majority of these indices do not provide correct estimates of real overlap, their utility for assessing mined land alpha diversity appears limited. A possible exception may be Schoener's index when overlaps are not expected to be below 7 percent or above 85 percent.

Evaluation

The value of similarity indices for the assessment of mined land alpha diversity has not yet been tested. If species number is a criterion for successful revegetation, the three coefficients recommended in Janson and Vegelius' (1981) study, Ochiai's coefficient, Dice's coefficient and Jaccard's coefficient seem well-suited for the assessment of species numbers or richness. If it is desirable to evaluate both species richness and evenness, Motyka and others' (1950) and Bray and Curtis' (1957) version of Sorensen's index and or Spatz' (1970) version of Jaccard's index have particularly good potential for the comparison of two communities. Chambers and Brown (1982) recommended their use for evaluating alpha diversity on revegetated mined lands in OSM Region IV.

The selection of Spatz' index or one of Sorensen's modifications would ultimately depend upon the objectives of the investigator. The general form of Sorensen's similarity index has been endorsed by Steward (1982) but Dr. Ed DePuit (personal communication) suggests the Spatz' index may provide a more reliable comparison of reference and revegetated areas.

The two types of indices place different emphasize on the quantitative and qualitative properties of revegetated and reference areas. In general, Spatz' index combines both quantitative and qualitative properties while Sorensen's modifications are more strictly quantitative (Mueller-Dombois and Ellenberg 1974). For example, Spatz' index places a greater emphasis on the comparison of the number of common and different species or life forms and the differences in importance values between individual species or life forms. Comparisons of revegetated and reference areas with several common species or life forms in which all of the common species or life forms have large importance values generally produce high similarity values when modifications of Sorensen's index are used. However, if the same areas also have species or life forms with smaller importance values that occur in only one or the other of the

areas, Spatz' index will produce a much smaller similarity value than Sorensen's modifications. The differences between these indices are illustrated in appendix III.

Because similarity indices furnish a single index value, their use would require the establishment of criteria for the determination of a "good" index value. Even the comparison of two highly similar communities often results in index values substantially lower than 1 (complete similarity). The index value obtained could be expected to vary according to the vegetation types under investigation. One method of obtaining a realistic "acceptable" index value would be to sample replicate areas within the reference area and to compute the similarity index for the replicates. This value would express the inherent similarity within the reference area. A value slightly lower than the one calculated for the reference area could then serve as the minimum similarity value for comparing the reference area to the revegetated area. Steward (1982) suggested that if several replicates were sampled within the reference area, similarity indices could be calculated between each of the replicates. A confidence interval could then be derived for the calculated similarity indices. The criterion for adequate alpha diversity would be that the similarity index calculated between the mean species or life form values of the reference and revegetated areas fall within the confidence interval calculated for the replicates.

CONCLUSIONS

A system of measurement used to compare the alpha diversity of a revegetated area to that of a reference area should include these attributes:

1. A "good" diversity measure should allow the direct comparison of two different communities—a reference area and a revegetated area. Ideally, the measure would produce only a single index.
2. The measure should be sensitive to changes in species or life form identities, and to species or life form importance values.
3. The measure should be equally effective with either life form or species data and adaptable to different types of importance measures (standing crop or cover).
4. A means of developing a standard of comparison for the measure should exist. For example, computing a similarity index from replicate samples within a reference area(s) provides an indication of the inherent similarity within the reference area that can be used as a standard of comparison for the revegetated area.
5. The measure should be easy to compute and understand.

Of the different types of diversity measures examined, only Motyka and others' and Bray and Curtis' version of Sorensen's and Spatz' version of Jaccard's index have all of the necessary properties. Diversity indices, in general, have several characteristics that are undesirable for evaluating mined land. The greatest limitation of diversity indices is that they cannot describe the specific apportionment of importance among species between two areas. Rank correlation tests appear to meet most of the criteria, however, they have certain restrictions that limit their use for evaluating mined land diversity. They provide only a relative comparison of species or life form apportionment and do not directly evaluate differences in species or life form identities.

Similarity indices, such as Motyka and others' and Bray and Curtis' version of Sorensen's index and Spatz' version of Jaccard's index have not received rigorous field tests, but conceptually, they are well suited for assessing mined land alpha diversity. Because they allow the sequential comparison of numerous different communities, namely, through cluster analysis, they can be used to synthesize information gathered from several different reference and revegetated areas, or information gathered on the same site over a period of time. They have excellent potential for developing idealized standards for particular community types, range sites, or habitat types within defined ecosystems.

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APPENDIX I. SAMPLE CALCULATION OF THE SHANNON DIVERSITY INDEX

A sample calculation for the Shannon index is given in table 1. The importance value used is dry weight production and the percentage of the importance value, p_i, is the percent production of each species or life form of the total production. Since the maximum value of H′ is equal to one, the H′ values obtained here, 0.872 for the revegetated area and 0.969 for the reference area, are actually very high. If it can be assumed that the calculated H′ value accurately depicts the diversity of the reference area, then the H′ value of the revegetated area would have to be within a certain limit of the reference area H′ in order to meet the diversity criteria. In interpreting and in calculating diversity indices, however, the constraints listed under the section on alpha diversity measures must be considered.

Table 1.—*A sample calculation of the Shannon index (lbs/acre = dry weight)*

Life form	Revegetated area			Reference area		
or species	lbs/acre	p_i	$-(p_i \log p_i)$	lbs/acre	p_i	$-(p_i \log p_i)$
1	553	0.200	0.140	524	0.177	0.133
2	479	0.173	0.132	348	0.117	0.109
3	234	0.084	0.090	441	0.149	0.123
4	625	0.226	0.146	563	0.190	0.137
5	351	0.127	0.114	197	0.066	0.078
6	26	0.009	0.018	151	0.051	0.066
7	108	0.039	0.055	94	0.032	0.048
8	84	0.030	0.046	175	0.059	0.073
9	67	0.025	0.039			
10	242	0.087	0.092			
11				269	0.091	0.095
12				43	0.014	0.026
13				123	0.042	0.058
14				36	0.012	0.023
Σ	2769	1.000	0.872	2964	1.000	0.969

APPENDIX II. TEST STATISTIC FOR SPEARMAN'S RANK CORRELATION COEFFICIENT—R_o AND A SAMPLE CALCULATION

The test statistic for Spearman's R_o, Spearman's R_s, is defined by the expression:

$$R = 1 - \frac{6\Sigma d}{n(n - 1)}$$

where:

d_i = the difference between the two ranks
n = the number of comparisons

The null hypothesis that we wish to test is that the species or life form importance values of the revegetated and reference areas are not independent of each other. (The importance values for the two areas are apportioned between the species or life forms in the same manner.) For a one-sided test of the null hypothesis:

Accept H_0 if $R < R$
Reject H_0 if $R > R$

The critical values of Spearman's rank correlation coefficient, the R_o values, are found in table 2.

An approximate t* value can also be calculated with which to test the null hypothesis. The t* value can be used in place of the critical R_o values for $n > 30$ and for probability levels other than those shown in table 2. For a one-sided test of the null hypothesis:

$$t^* = R\sqrt{(n - 2)/(1 - R)}$$

Table 2.—*Critical values of Spearman's rank correlation coefficient*

n	$\alpha = 0.10$	$\alpha = 0.05$	$\alpha = 0.02$	$\alpha = 0.01$
5	0.900	—	—	—
6	0.829	0.886	0.943	—
7	0.714	0.786	0.893	—
8	0.643	0.738	0.833	0.881
9	0.600	0.683	0.783	0.833
10	0.564	0.648	0.745	0.794
11	0.523	0.623	0.736	0.818
12	0.497	0.591	0.703	0.780
13	0.475	0.566	0.673	0.745
14	0.457	0.545	0.646	0.716
15	0.441	0.525	0.623	0.689
16	0.425	0.507	0.601	0.666
17	0.412	0.490	0.582	0.645
18	0.399	0.476	0.564	0.625
19	0.388	0.462	0.549	0.608
20	0.377	0.450	0.534	0.591
21	0.368	0.438	0.521	0.576
22	0.359	0.428	0.508	0.562
23	0.351	0.418	0.496	0.549
24	0.343	0.409	0.485	0.537
25	0.336	0.400	0.475	0.526
26	0.329	0.392	0.465	0.515
27	0.323	0.385	0.456	0.505
28	0.317	0.377	0.448	0.496
29	0.311	0.370	0.440	0.487
30	0.305	0.364	0.432	0.478

From Olds (1938).

The calculated t* value is compared with a value for the t_{n-2} obtained from a t-table for one-sided tests (refer to table 3).

Accept H_o if $t^* \leq t_{n-2}$

Reject H_o if $t^* > t_{n-2}$

An example of a comparison between a revegetated area and a reference area using Spearman's R_o is given in table 4. The species or life forms from each area are first ranked according to the magnitude of their importance values. If species or life forms exist in one area but not the other, they are assigned the average of the lowest possible rankings for the area in which they do not exist. For example, the revegetation area shown in table 4 was missing four species or life forms that existed in the reference area. The lowest possible rankings for the revegetated area would be 11, 12, 13, and 14. The average of these four values, 12.5, is assigned to the species or life forms that are missing in the revegetated area.

Table 3.—*t-Distribution values for values for various levels of n, or degrees of freedom, df, for a one-sided test*

	Probability of a larger value of t, sign considered								
df	0.25	0.2	0.15	0.1	0.05	0.25	0.01	0.005	0.0005
1	1.000	1.376	1.963	3.078	6.314	12.706	31.821	63.657	636.619
2	.816	1.061	1.386	1.886	2.920	4.303	6.965	9.925	31.598
3	.765	.978	1.250	1.638	2.353	3.182	4.541	5.841	12.941
4	.741	.941	1.190	1.533	2.132	2.776	3.747	4.604	8.610
5	.727	.920	1.156	1.476	2.015	2.571	3.365	4.032	6.859
7	.711	.896	1.119	1.415	1.895	2.365	2.998	3.449	5.405
8	.706	.889	1.108	1.397	1.860	2.306	2.896	3.355	5.041
9	.703	.883	1.100	1.383	1.833	2.262	2.821	3.250	4.781
10	.700	.879	1.093	1.372	1.812	2.228	2.764	3.169	4.587
11	.697	.876	1.088	1.363	1.796	2.201	2.718	3.106	4.437
12	.695	.873	1.083	1.356	1.782	2.179	2.681	3.055	4.318
13	.694	.870	1.079	1.350	1.771	2.160	2.650	3.012	4.221
14	.692	.868	1.076	1.345	1.761	2.145	2.624	2.977	4.140
15	.691	.866	1.074	1.341	1.753	2.131	2.602	2.947	4.073
16	.690	.865	1.071	1.337	1.746	2.120	2.583	2.921	4.015
17	.689	.863	1.069	1.333	1.740	2.110	2.567	2.898	3.965
18	.688	.862	1.067	1.330	1.734	2.101	2.552	2.878	3.922
19	.688	.861	1.066	1.328	1.729	2.093	2.539	2.861	3.883
20	.687	.860	1.064	1.325	1.725	2.086	2.528	2.845	3.850
21	.686	.859	1.063	1.323	1.721	2.080	2.518	2.831	3.819
22	.686	.858	1.061	1.321	1.717	2.074	2.508	2.819	3.792
23	.685	.858	1.060	1.319	1.714	2.069	2.500	2.807	3.767
24	.685	.857	1.059	1.318	1.711	2.064	2.492	2.797	3.745
25	.684	.856	1.058	1.316	1.708	2.060	2.485	2.787	3.725
26	.684	.856	1.058	1.315	1.706	2.056	2.479	2.779	3.707
27	.684	.855	1.057	1.314	1.703	2.052	2.473	2.771	3.690
28	.683	.855	1.056	1.313	1.701	2.048	2.467	2.763	3.674
29	.683	.854	1.055	1.311	1.699	2.045	2.462	2.756	3.659
30	.683	.854	1.055	1.310	1.697	2.042	2.457	2.750	3.646
40	.681	.851	1.050	1.303	1.684	2.021	2.423	2.704	3.551
60	.679	.848	1.046	1.296	1.671	2.000	2.390	2.660	3.460
120	.677	.845	1.041	1.289	1.658	1.980	2.358	2.617	3.373
∞	.674	.842	1.036	1.282	1.645	1.960	2.326	2.576	3.291

Table 4.—*An example of ranked revegetated and reference areas A_1 and A_2, the difference between the two, d_i, and the difference squared, d_i^2 (lbs/acre = dry weight)*

Life form or species	Revegetated area lbs/acre	A_1	Reference area lbs/acre	A_2	d_i	d_i^2
1	553	2	524	2	0	0
2	479	3	348	4	1	1
3	234	6	441	3	3	9
4	625	1	563	1	0	0
5	351	4	197	6	-2	4
6	26	10	151	8	2	4
7	108	7	94	10	3	9
8	84	8	175	7	1	1
9	67	9		13.5	-4.5	20.25
10	242	5		13.5	-8.5	72.25
11		12.5	269	5	7.5	56.25
12		12.5	43	11	1.5	2.25
13		12.5	123	9	3.5	12.25
14		12.5	36	12	5	0.25
Σ						191.50

The difference between the two ranks of species or life forms found in the two areas, d_i, is obtained by subtracting rank 1, A_1, from rank 2, A_2. The values of d_i are then squared and summed. Once these values have been obtained, the test statistic for Spearman's rank correlation is computed:

$$R = 1 - \frac{6\Sigma d_i^2}{n(n^2 - 1)}$$

$$= 1 - \frac{6(191.50)}{14(14^2 - 1)}$$

$$= 1 - \frac{1149}{2730}$$

$$= 1 - .421$$

$$= 0.579$$

The critical value for R_o with $n = 14$ and $\alpha = 0.10$ is 0.457 (see table 2). Since the test statistic, $R_s = 0.579$, is greater than the critical value, $R_o = 0.457$, the null hypothesis is rejected. The revegetated area presented in this example was independent of the reference area at $\alpha = 0.10$. According to this test, the importance values for the two areas were not apportioned in a similar manner.

A t* value can also be calculated with which to test the hypothesis:

$$t^* = R_s\sqrt{(n-2)/(1-R_s^2)}$$

$$= 0.579\ \sqrt{(14-2)/(1-0.579^2)}$$

$$= 2.459$$

Because the value for $t_{12}(.05)$, 1.782, is less than the calculated t* value, 2.459, the null hypothesis is again rejected.

APPENDIX III. COMPARISON OF THE CALCULATION OF MOTYKA AND OTHERS' (1950) AND BRAY AND CURTIS' (1957) VERSION OF SORENSEN'S INDEX AND SPATZ' (1970) VERSION OF JACCARD'S INDEX

Tables 5, 6, and 7 present examples of the calculation of the three different indices. The importance values used are standing crop values (lbs/acre dry weight). Table 5 illustrates the difference between common and unique species in a reference and revegetated area and shows how they are used to calculate Motyka and others' version of Sorensen's index. Tables 6 and 7 illustrate the calculation of the three different indices and the effect of differences in life form importance values.

Table 5.—*An example of the common and unique species of a revegetated and reference area and the calculation of Motyka and others' version of Sorensen's index (lbs/acre = dry weight)*

Species	Revegetated area (MA) lbs/acre	Common species (MA) lbs/acre	Common species (MB) lbs/acre	Reference area (MB) lbs/acre
1		553	524	
2		479	348	
3		234	441	
4		625	563	
5		351	197	
6		26	151	
7		108	94	
8		84	175	
9	67			
10	242			
11				269
12				43
13				123
14				36
Total	309			471

Calculation of Motyka and others' version of Sorensen's index.

$$IS_{MO} = \frac{2\ MW}{MA + MB}$$

$MW = 524 + 348 + 234 + 563 + 197 + 26 + 94 + 84 = 2070$

$MA = 553 + 479 + 234 + 625 + 351 + 26 + 108 + 84 + 67 + 242 = 2769$

$MB = 524 + 348 + 441 + 563 + 197 + 151 + 94 + 175 + 269 + 43 + 123 + 36 = 2964$

$$IS_{MO} \quad \frac{2(2070)}{2769 + 2964} \quad .72 \times 100 = 72\%$$

Table 6.—*Example of high similarity between a revegetated area and a reference area as compared by Motyka and others' and Bray and Curtis' version of Sorensen's index and Spatz' version of Jaccard's index (lbs/acre = dry weight)*

Life form	Revegetated area		Reference area	
	lbs/acre	Percent composition	lbs/acre	Percent composition
Annual grass	187	15	28	2
Perennial cool season bunchgrass	361	29	503	36
Perennial warm season bunchgrass	274	22	391	28
Perennial warm season rhizomatous grass	162	13	154	11
Annual herbs	199	16	14	1
Perennial herbs	62	5	196	14
Biennial herbs			28	2
Broadleaf deciduous shrubs			84	6
Total	1,245	100	1,398	100

Motyka and others' version of Sorensen's index:

$$IS_M = \frac{2\,MW}{MA + MB}$$

MW = 28 + 361 + 274 + 154 + 14 + 62 = 893

MA = 187 + 361 + 274 + 162 + 199 + 62 = 1245

MB = 28 + 503 + 391 + 154 + 14 + 196 + 28 + 84 = 1398

$$IS_M = \frac{2(893)}{1245 + 1398} = 0.68 \times 100 = 68$$

Bray and Curtis' version of Sorensen's index:

IS_{BC} = MW(percent)

MW = 2 + 29 + 22 + 11 + 1 + 5 = 70

IS_{BC} = 70(percent) = 70%

Spatz' version of Jaccard's index:

$$IS_{SP} = R \times \frac{MC}{MA + MB + MC}$$

$$IS_{SP} = 0.37 \times \frac{192}{200} = 0.36$$

$$R = \frac{2 + 15 + 29 + 36 + 22 + 28 + 11 + 13 + 1 + 16 + 5 + 14}{8}$$

$$\frac{0.13 + 0.80 + 0.79 + 0.85 + 1.00 + 0.56}{8} = 0.37$$

Table 7.—*Example of low similarity between a revegetated area and a reference area as compared by Motyka and others' and Bray and Curtis' version of Sorensen's index and Spatz' version of Jaccard's index (lbs/acre = dry weight)*

Life form	Revegetated area		Reference area	
	lbs/acre	Percent composition	lbs/acre	Percent composition
Annual grass	373	25	28	2
Perennial cool season bunchgrass			483	37
Perennial warm season bunchgrass	194	13	345	26
Perennial warm season rhizomatous grass	448	30	148	11
Annual herbs	433	29	13	1
Perennial herbs	45	3	188	14
Biennial herbs			27	2
Broadleaf deciduous shrubs			80	6
Total	1,493	100	1,312	99

Motyka and others' version of Sorensen's index:

$$IS_{MO} = \frac{2\ MW}{MA + MB}$$

$$MW = 28 + 194 + 148 + 13 + 45 = 428$$

$$MA = 373 + 194 + 448 + 433 + 45 = 1493$$

$$MB = 28 + 483 + 345 + 148 + 13 + 188 + 27 + 80 = 1312$$

$$IS_{MO} = \frac{2(428)}{1493 + 1312} = 0.30 \times 100 = 30\%$$

Bray and Curtis' version of Sorensen's index:

$$IS_{BC} = MW(\text{percent})$$

$$MW = 2 + 13 + 11 + 1 + 13 = 30$$

$$IS_{BC} = 30(\text{percent}) = 30\%$$

Spatz' version of Jaccard's index:

$$IS_{SP} = R \times \frac{MC}{MA + MB + MC} \times 100 \qquad IS_{SP} = 0.15 \times \frac{155}{200} \times 100 = 12\%$$

$$R = \frac{2 - 25 + 13 - 26 + 11 - 30 + 1 - 29 + 3 - 14}{8}$$

$$= \frac{0.08 + 0.5 + 0.37 + 0.03 + 0.21}{8} = 0.15$$

APPENDIX IV. SELECTION OF IMPORTANCE VALUES

The selection of importance values for use with rank correlation tests, diversity indices, or similarity indices deserves careful consideration. Production/standing crop is normally the best measure of a species' importance; it indicates both the species' biological activity and the amount of the communities' resources that a species utilizes. The measure has little ambiguity due to collection methods and is directly comparable between species. Density, however, is an inappropriate measure in many communities because of the huge differences in the contribution of individuals of different life-forms (trees versus herbs) to the structure and function of the community. When the community is comprised primarily of one life-form, such as shrubs, then density may be an appropriate importance measure. The determination of a meaningful cover value to express importance may be difficult in multilayered communities. It is best to restrict the use of cover in the calculation of importance value to fairly open communities with a very few layers.

Chambers, Jeanne C. Measuring species diversity on revegetated surface mines: an evaluation of techniques. Res. Pap. INT-322 Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 15 p.

Three commonly used measures of plant species diversity are reviewed: (1) diversity indices, (2) rank correlation coefficients, and (3) similarity indices. The suitability of each type of measure for assessing species diversity on mined lands is evaluated and applications of the Shannon-Weiner diversity index, Spearman's rank order correlation coefficient, Motyka and others' and Bray and Curtis' version of Sorensen's similarity index and Spatz' version of Jaccard's index are presented. Of the three types of diversity measures evaluated, only similarity indices allow direct comparisons of two different communities and are sensitive to change in species or life form identities. They can be used with either life form or species data and with different types of importance measures. Similarity indices also permit the development of a standard of comparison.

KEYWORDS: revegetation, species diversity, diversity indices, rank correlation tests, similarity coefficients

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Understory Vegetation Inventory: An Efficient Procedure

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RESEARCH SUMMARY

The Understory Vegetation Inventory Procedure used on Forest Survey plots provides some basic information about the plant community that, when combined with other information, can be used for wildlife habitat and forage evaluation, grazing use potential, potential climax and seral stage of vegetation, and estimation of land productivity in terms of biomass.

Understory Vegetation Inventory: An Efficient Procedure

Renee O'Brien
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INTRODUCTION

To meet the requirements for national assessments mandated by the Forest and Rangeland Renewable Resources Planning Act of 1974 and other legislation, the USDA Forest Service's Forest Survey has expanded traditionally timber-oriented inventories to include data on understory vegetation. Such information, in combination with overstory data, provides a structural picture of the plant community that can be used in many disciplines with broad application for wildlife habitat and forage evaluation, grazing use potential, and estimation of land productivity in terms of biomass.

Several schemes for sampling understory vegetation provide useful information (Cost 1979; Pearson and Sternitzke 1974; USDA Forest Service 1980, 1981a, 1982a). Each has been developed in relation to the vegetational characteristics peculiar to a general geographic location, attendant wildlife species, land use patterns, and according to the needs and demands of data users. To be suitable for use by Forest Survey, a procedure should:

1. Be adaptable to an extensive, sample-based inventory.
2. Be easily integrated into the existing physical procedures and time frame of Forest Survey.
3. Consist of objective observations that personnel with limited taxonomic skills can perform.
4. Be applicable throughout the field season (April through October).
5. Cause no disturbance to vegetation on permanent plots.

The procedure presented here was developed for use in the Rocky Mountains (fig. 1) by Forest Survey at the Intermountain Forest and Range Experiment Station. It is an adaptation of several established methods.

Forest Survey conducts an extensive inventory that provides data for RPA assessments, national level decisionmaking, and State level analysis of the resource situation. The extensive nature of the inventory lends itself to a brief and simple estimate of the characteristics of the vegetation. In the Intermountain area, a list of major species of a site and an estimate of composition and vertical diversity provides the basic structural picture needed for general biomass, wildlife habitat, and range interpretations.

PROCEDURE

The Understory Vegetation Inventory Procedure was used in the 1981 inventory of State and private lands in Idaho, in 1982 in a similar inventory of Colorado, and in 1983 in the South Dakota and Wyoming inventories. The procedure proved efficient and satisfactory in providing some basic information about the plant community at each field location sampled by Forest Survey crews. Such information is sufficient for most general understory vegetation interpretations.

Made up of two parts, the Understory Vegetation Inventory uses a 1/20-acre circular plot surrounding each of the five cluster sample points used for the timber inventory. A more complete explanation of this procedure can be found in the Forest Survey field manuals (USDA Forest Service 1981b, 1982b, 1983a, b).

Part I provides **individual species** information. For each of the four plant groups—trees, shrubs, forbs, and graminoids—up to four species occurring with a crown canopy cover of at least 5 percent are recorded. Crown canopy cover is the area of ground surface covered by the canopy of a plant. Canopy coverage for each species recorded is visually estimated and assigned one of the following coverage classes (Daubenmire 1959):

Crown canopy cover class codes	Percent crown canopy coverage
1	5
2	6- 25
3	26- 50
4	51- 75
5	76- 95
6	96-100

Rarely do more than four species occur for any one plant group with 5 percent crown canopy cover or greater. The 5 percent canopy cover stipulation reduces the number of plant species requiring identification by field crews. A crown canopy cover class is assigned each species recorded. Part I provides an indication of the major species composition and horizontal diversity of a plot.

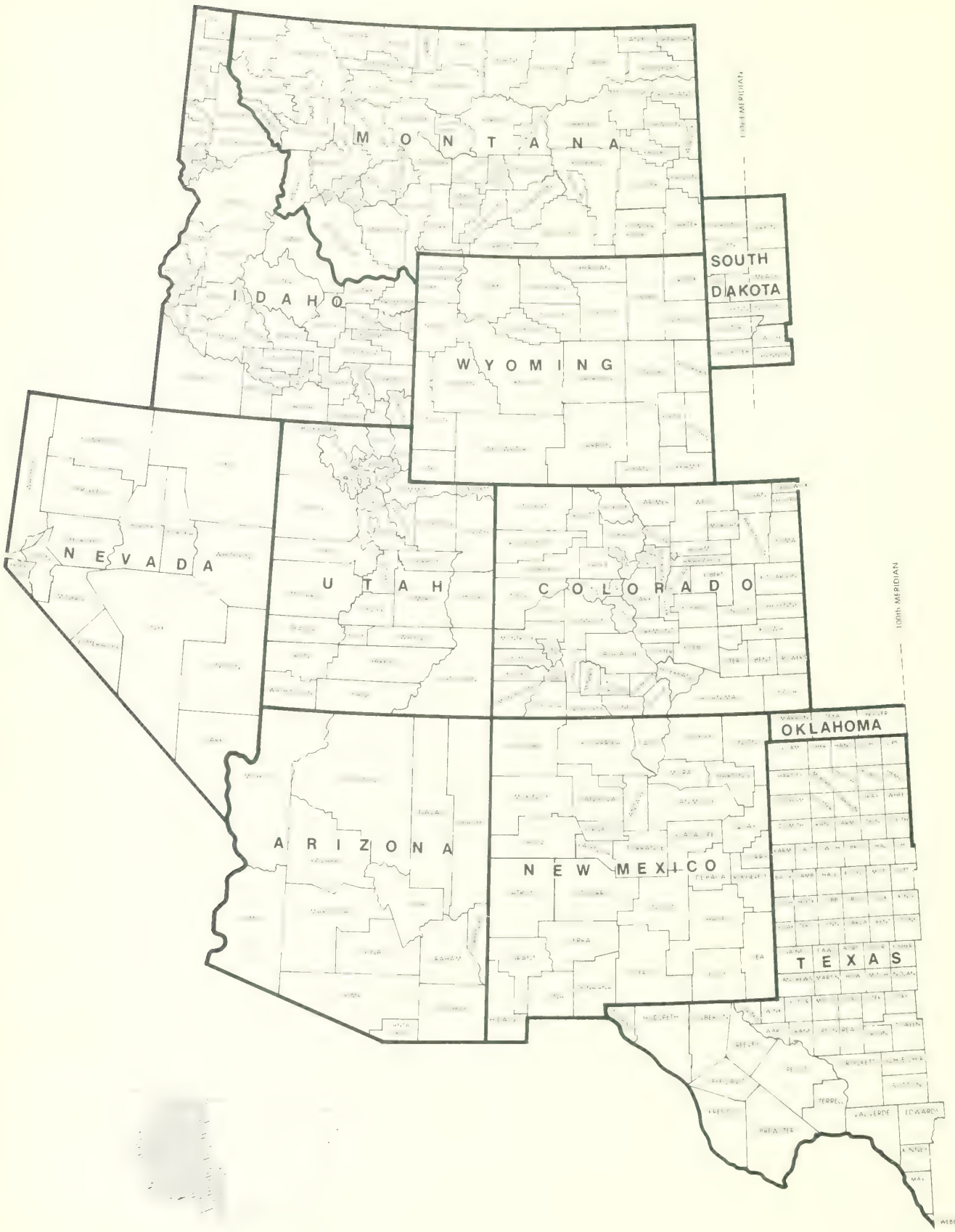

Figure 1.—Map of area inventoried by Forest Survey.

The vertical diversity of vegetation on a plot is described by the assignment of one of three vegetational layers to each species recorded:

Layer 1 – (0-1.5 ft)
Layer 2 – (1.6-6 ft)
Layer 3 – (6.1+ ft)

Confining the species list to only the predominantly occurring plants makes the procedure fast and easy and still provides a picture of the basic composition of the understory vegetation.

Part II provides **plant group** information that, when combined with the overstory tree data, will provide a vegetational profile of the plot. Part II entails an assessment of the plant groups on the plot by layer. For each of the three layers previously referred to, a cover class is assigned to any of the four plant groups that occurs on the plot. This characterization by plant group provides a slightly different picture than the species list from Part I, and includes plants not abundant enough to be recorded by species, but which contribute to the vegetational structure when grouped.

DISCUSSION

Information collected with the Understory Vegetation Inventory Procedure, when combined with the overstory data taken on Forest Survey plots, will provide a structural profile of the plant community for each location. This profile can be interpreted in many ways for use in various disciplines.

For example, the data may be used to obtain estimates of area of wildlife habitat. Computer programs are available at this time such as WILD RAM (Winn and others n.d.) used by Forest Service Intermountain Region and WFHR (Prather and Burbridge n.d.) used by Forest Service Northern Region. These programs use general timber stand variables such as forest type, size class, age, canopy cover, and other stand features, to predict potential wildlife use of a site for feeding, breeding, or resting. More specific types of designations could be made using the understory structure and composition information provided by inventory data. Correlations of animal species with timber site capacity and animal species diversity with stand condition may also be developed.

The understory vegetation information combined with habitat type designations such as those presented by Pfister (1976) would give an indication of the potential climax vegetation and seral stage of the plant community. This information would be useful for many range, wildlife, and silvicultural interpretations.

The data may also be useful in conversion to estimates of biomass. Some biomass conversion factors or equations have been developed using cover and height information of either plant groups or individual species (Brown and Marsden 1976; Alexander 1978; Olson and Martin 1981). For range managers, the data can provide a list of preferred forage species present or relative amounts of herbaceous or browse materials available. Such information should be useful in evaluating the effects of various resource interactions.

EXAMPLE

An illustration of the vegetation occurring on one five-point location cluster (fig. 2) would have a corresponding entry such as the example in figure 3. One way of summarizing the combined overstory and understory data of a location is the vegetation profile (fig. 4). This profile plots height of vegetation over percent canopy cover of the four different plant classes—trees, shrubs, forbs, and graminoids.

Several observations can be made about the vegetational structure of this plot. The plot has extensive grass forb cover that could make it a feeding area for deer and elk. The presence of the forb *Arnica cordifolia*, which is preferred by elk (USDA Soil Conservation Service 1982), makes this type of condition more favorable for use by elk. This condition would not be preferred for hiding cover for deer and elk because of the inadequate tree and shrub cover between 2 and 6 feet. Thermal cover requirements for elk and deer are not met because [illegible] probably be used by deer and elk only for transitory feeding.

The structural diversity of the vegetation on this plot—grass forb, shrub, seedling, and multistoried canopy layers all present—indicates that the area could be used by many species of birds. The bird population could include insect gleaners feeding in the tree and shrub layers and on the ground, and species that breed in dense low tree and high shrub canopies. The high amount of herbaceous cover on the plot indicates that forage is available for domestic animals although none of the species listed are preferred by livestock (USDA Soil Conservation Service 1982).

The vegetational information of a plot is not meant to stand alone. Usually the profiles are developed for a group of field locations that meet specific criteria. In addition, the vegetation profile is meant to be used with other data collected such as elevation, slope, aspect, size of condition, nearness to roads, nearness to water, and snags and other special features for wildlife, which are important but are not within the scope of this paper.

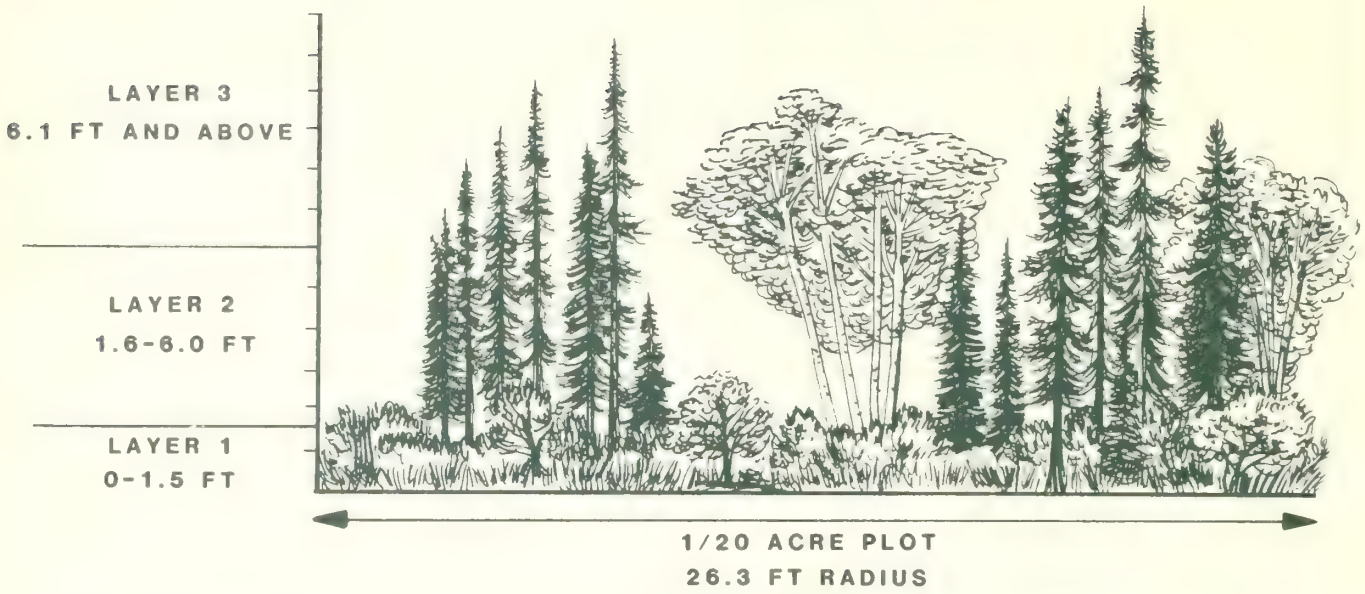

Figure 2.—Illustration of the understory vegetation on one point of the five-point cluster.

POINT NUMBER	PART 1 - SPECIES LIST BY COVER CLASS AND LAYER												PART 2 - PLANT GROUP COVER CLASS BY LAYER				
	TREES			SHRUBS			FORBS			GRAMINOIDS			Layer	TREES	SHRUBS	FORBS	GRAMINOIDS
	Species	Cover	Layer	Species	Cover	Layer	Species	Cover	Layer	Species	Cover	Layer					
	XXXXX	X	X	XXXXX	X	X	XXXXX	X	X	XXXXX	X	X		X	X	X	X
1	ABGR	3	3	VAME	3	2	GATR	2	1	CARU	4	1	3 (6.1' +)	4	2	0	0
	PSME	1	3	ALSI	2	3	VIOR	3	1				2 (1.6-6')	1	3	0	0
	LAOC	2	2				ARCO	2	1				1 (0-1.5')	0	0	4	4
							SMRA	2	1								

LAOC - Larix occidentalis
ABGR - Abies grandis
ALSI - Alnus sinuata
PSME - Pseudotsuga menziesii
VAME - Vaccinium membranaceum
GATR - Galium triflorum
CARU - Calamagrostis rubescens
ARCO - Arnica cordifolia
VIOR - Viola orbiculata
SMRA - Smilacina racemosa

Figure 3.—Example of the field data form entry for the vegetation on the plot illustrated above.

Figure 4.—Vegetational profile.

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O'Brien, Renee; Van Hooser, Dwane D. Understory vegetation inventory: an efficient procedure. Research Paper INT-323. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 6 p.

Presents a procedure for describing understory vegetation on forested plots. Plant species with 5 percent or greater canopy cover are listed and assigned a canopy cover class and a height layer class. Each of the four plant groups—trees, shrubs, forbs, and graminoids—are assigned a canopy cover class by layer. These data are to be combined with tree canopy and other stand data for use in range, wildlife, biomass, and silvicultural interpretations.

KEYWORDS: understory vegetation inventory, Forest Survey techniques, vegetational structure, canopy cover, plant groups

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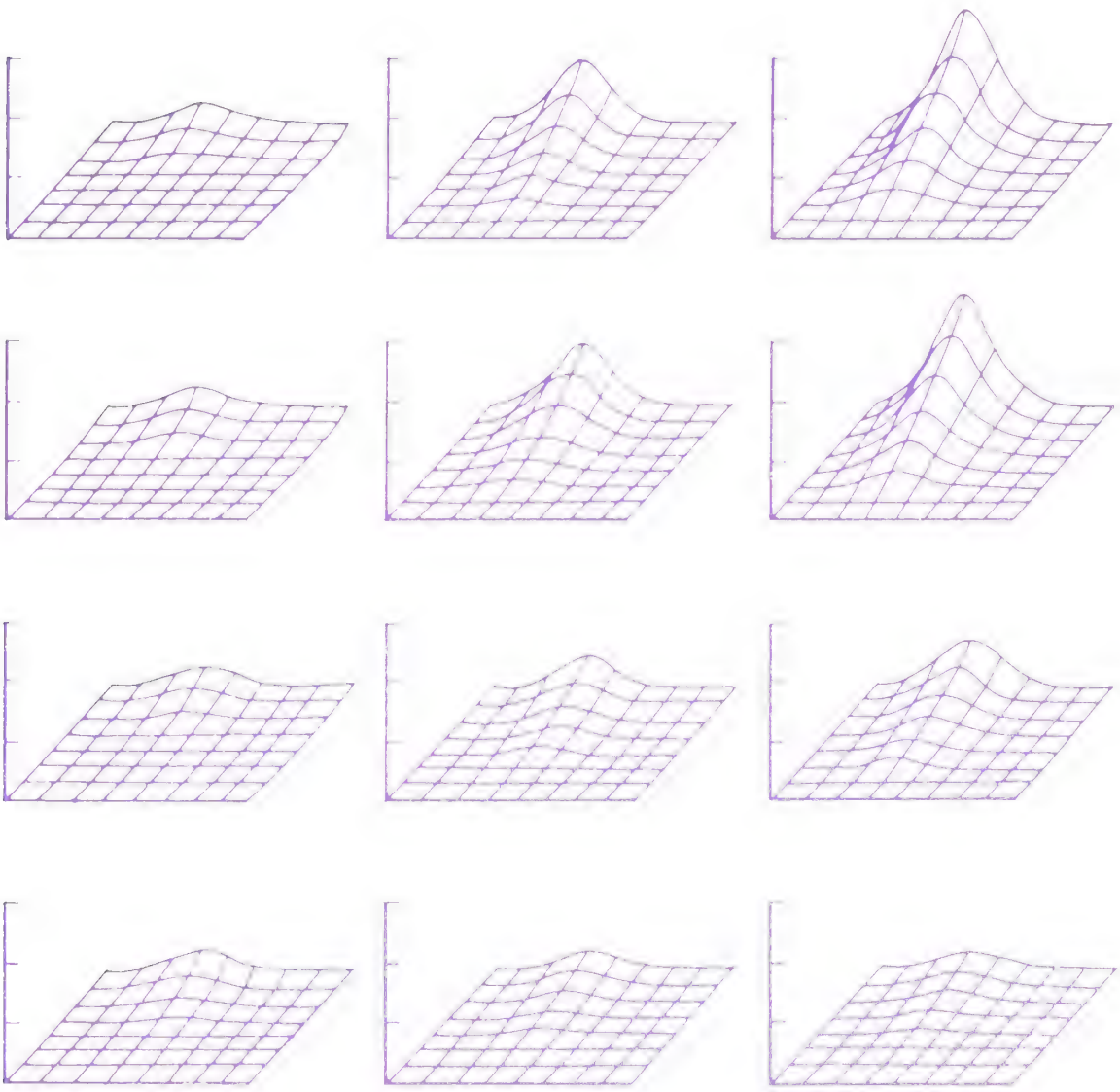
Development of Structured Regression Hypotheses / Interactive Descriptive Geometry Through Five Dimensions

Chester E. Jensen



THE AUTHOR

CHESTER E. JENSEN, retired, served as principal statistician for the Intermountain Forest and Range Experiment Station from 1967–80. He held the same position at the Northeastern and Central States Forest Experiment Stations prior to coming to the Intermountain Station. Mr. Jensen can be reached by mail through the Intermountain Station or by telephone at 801–621–0791.

ACKNOWLEDGMENTS

A large vote of thanks for the multitude of "live data" examples used in the text is due the author-scientists noted in each case. Their professional inputs were fundamental to compilation of the models generated.

My profound appreciation is extended also, to the many scientists who graciously provided critical reviews of the past methods manuscripts summarized here, Dr. F. Thomas Lloyd, statistician (U.S. Forest Service, Southeastern Station), was perhaps the most consistent contributor in this respect.

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RESEARCH SUMMARY

Regression hypotheses admitted to statistical evaluation should, of course, be germane to relations between the variables considered. This constraint is easily violated with the screening of arbitrarily adopted sets of hypotheses. Sequential polynomials in additive models, for example, may include components that are not commensurate with expectation (prior knowledge) and may not include those that are (e.g., unique interaction terms) and, since the analytical results from the screening of meaningless hypotheses may themselves be meaningless, there is substantial incentive for serious preanalysis consideration of the hypotheses to be evaluated.

Where prior knowledge is reasonably strong, the relation under consideration is highly interactive and/or has unique curve form or intercept constraints, the development of a fairly specific (structured) hypothesis is probably advisable. This can be evaluated on pertinent data sets not involved in the hypothesis development.

Prior knowledge information sources can include theory resulting from past investigation as well as information derived from data sets or parts of such data sets devoted to hypothesis development. Methods for developing multidimensional graphic models from two-dimensional effects found in partitioned data and for incorporating even complex constraints are shown in both contrived- and live-application examples.

Mathematical descriptors for the resulting graphic models are assembled using two families of curves: X^n, $n \geq 1$; and e^{-K}, a highly manipulable function for bell-shaped curves or portions thereof. In either case, the X-axis for each two-dimensional effect is altered as needed to orient the curve in the upper-right quadrant. The analyst then simply compares a normalized-scale version of the resulting curve with graphed standard curves, Standards, and locates the two adjacent ones most nearly like his own in shape. Interpolation between the curves and their associated parameters, results in identification of the function for the best matching curve offered by the system.

The alternative of using a completely automated X-transform selection system from the Standards was considered at length. But, inability to define criteria (including the fitting process) that always result in the best choice of descriptor, regardless of data distribution or analytical objectives, resulted in retention of the less sophisticated, but still completely flexible graphic comparison technique shown herein. Methods of use are fairly well documented for each of the graphed-relation examples, which vary from two to five dimensions.

The mathematical descriptors can be regarded as pertinent hypotheses to be evaluated on data sets not used in their development. The evaluation on a single data set can involve a simple scale adjustment in $Y = b$ (hypotheses), as shown herein, or a variety of more complex testing formats (not shown) depending on complexity of the hypothesis itself, capacity of the analyst to linearize it, and/or on the nature of the fitting system adopted (linear, nonlinear). Also evaluation can be based on performance statistics compiled from real-world applications of the hypothesized descriptors.

Experience gained from the presentation of a dozen short courses covering methodology through the fourth dimension, suggests that this material can be assimilated by researchers with only college algebra-level mathematical background and brief training in the operation of programable electronic calculators. Also note that the graphic presentation scheme for the four- and five-dimensional relations used in this paper can, with nominal explanation, be readily interpreted by land managers having little or no interest in the complex mathematical descriptors that may be involved.

Development of Structured Regression Hypotheses/ Interactive Descriptive Geometry Through Five Dimensions

Chester E. Jensen

INTRODUCTION

Applications of statistics reported in biological literature were found by Mead and Pike (1975) to contain some prevalent and potentially damaging oversights. Among other things, they noted that, when transformations were used, simple polynomials predominated and seem to be used as the simplest readily available smoothing curve, without any appeal to their theoretical properties as approximations to the true response function. From this, it appears that analysts are inclined to adopt polynomials as a convenient curve-form panacea for all regression hypotheses rather than undertake purposeful preanalysis development of hypotheses specific to the relation under study.

In the presumed presence of incentive for analysts to follow technical direction, these findings suggest that this is the current (1975, at least) state of regression art insofar as applied statistics is concerned. One need only consult related text material to verify the notion. **Hypothesis development** is simply not a topic covered. Rather, integral polynomials are usually presented as a package of ready-made hypotheses that can be explored sequentially and mechanically using least squares fitting procedure. Discussion covering the inclusion of known constraints in these hypotheses is generally limited to that of the simple intercept. It is seldom, if ever, mentioned that the polynomials, or log-transforms, etc. cannot be presumed to provide adequate curve-form representation for all hypotheses. And, it is pertinent to note that failure to discuss hypothesis development and its potentially complex outcomes in text material constitutes *de facto* disapproval of any but simpler hypotheses, such as those by polynomials.

All told, there is ample cause for the hypothesis-related problems identified by Mead and Pike (1975) and attributed to authors of biological research papers. It would seem, however, that the source of the problem might more nearly be associated with limitations in text material and statistical curricula than with oversights by users of currently proffered statistical methodology.

An effort is made in this paper to initiate solutions to the hypothesis development problem through discussion and by showing analysts how to develop preanalysis hypotheses graphically, regardless of complexity, from accumulated knowledge and existing data. For biological subject matter, these hypotheses will be curvilinear and highly interactive as often as not.

Mathematical formulation of graphed hypotheses is accomplished through use of two families of curves: X^n, $n \geq 1$ (revamped herein from Jensen and Homeyer 1970); and $e^{-\lambda}$ (Jensen 1979), a highly manipulable function for bell-shaped curves or parts thereof. Descriptor development can be accomplished by analysts with a knowledge of basic algebra and access to a programable calculator.

HYPOTHESIS DEVELOPMENT, GENERAL

A condition for valid statistical evaluation of hypotheses is that they be developed independently of data used for evaluation. So, the analyst's first undertaking in a regression analysis should be to establish the strongest possible concept of the underlying form of the relation from accumulated knowledge on the relations being investigated. It can be anticipated for a broad array of problems that these concepts will vary from extremely weak, with little or no basis for form definition, to very firm expectations for even specific algebraic forms.

In the weak-concept case, there is little reason to allow for any but simple curve-form hypotheses. Low-order polynomials in a linear model will probably suffice. Where well-established algebraic forms already exist for the form of the relation, the exact hypothesis is already available and evaluation can be initiated. The more common and perhaps more challenging circumstance, however, involves some intermediate level of prior knowledge where the analyst is sure of some elements in the relation being considered and less sure of others. His or her deliberations on the nature of the relation may result directly in a mathematical hypothesis or, more commonly, they may result in a graphed form wherein the analyst imposes reasonable intercept-, form-, and scale-constraints. These elements of the resulting graph, then, must be represented with suitable mathematical accuracy to establish the final intermediate-strength hypothesis.

If the graphed hypothesis involves unique curve forms, substantial effort might be required to search through **existing functions** like those in the list provided by Mead and Pike (1975), for those with the capacity to mimic unique forms of the hypothesis. (Note that mathematical descriptors should meet the acceptance criteria of the analysts involved [Bartlett 1947; Draper and Hunter 1969]).

A generally more efficient alternative may be that of **analyst-developed** functions to describe graphed hypotheses. Relatively simple methods for describing even complex multidimensional curvilinear interactions are included in this paper. Curves of only two classes are utilized: X^n, $n \geq 1$; and the very versatile three-parameter bell-shaped function e^{-K}. Methods and related examples shown include a variety of research applications to lend realism to the instruction. Additional research applications not cited in the text are given under Additional References to provide the reader with the opportunity for expanded self-study of descriptor development.

Given a mathematical hypothesis, it can be evaluated using data sets not used in its development. The evaluation can vary from a test of general performance in $y = b$ (hypotheses), as shown herein, to more complex formats designated to test performance of individual components of the hypothesis. The testing format adopted is likely to depend on the complexity of the hypothesis itself, the capacity of the analysts to linearize it, and/or on the nature of the fitting system to be used (linear, nonlinear). Also evaluation can be based on performance statistics compiled over repeated real-world applications of the hypothesized descriptor. See Mosteller and Tukey (1977) and Box, Hunter, and Hunter (1978) for discussion of empirical and structural (mechanical) models, and fitting systems, etc.

GRAPHIC HYPOTHESIS DEVELOPMENT - TWO DIMENSIONS

Accumulated knowledge on the general nature of the regression relation under consideration may be used to enhance the derivation of finite graphed hypotheses from data. A common analytical ploy is to dedicate part (perhaps half) of a current data set to the development of a hypothesis, reserving the rest for hypothesis evaluation.

To illustrate, accumulated knowledge regarding the relation between Y and X is such that the curve is expected to pass through the origin, to have a positive slope over X, and to be linear- to concave-upward in form. Within these constraints, a specific estimate of the true shape of the relation is developed from half of a current data set (fig 1).

Here, the analyst visually estimates the curve form expressed in the data and simultaneously draws and hand-fits the form to the data by approximate least deviations (Karst 1958). All of this is accomplished within the constraints of expectation.

In another case, prior knowledge leads to a strong expectation for a positive intercept and, above this, a sigmoid upward to the right with Y asymptoting at a value of 100 percent over large values of X. Within these constraints, a specific estimate is again developed from half of a current data set (fig. 2).

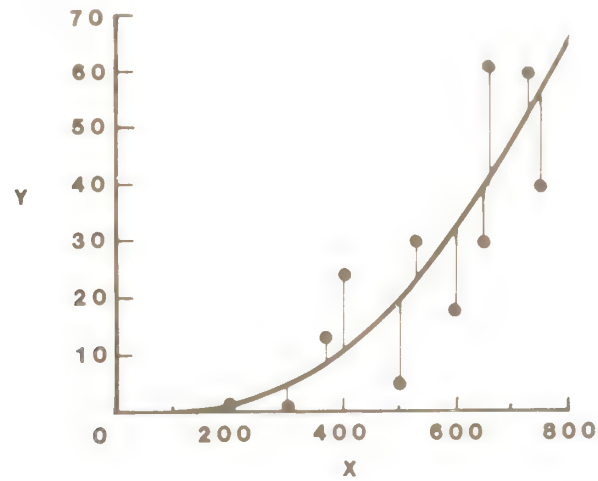

Figure 1.—A graphed estimate of the true form of the relation between X and Y.

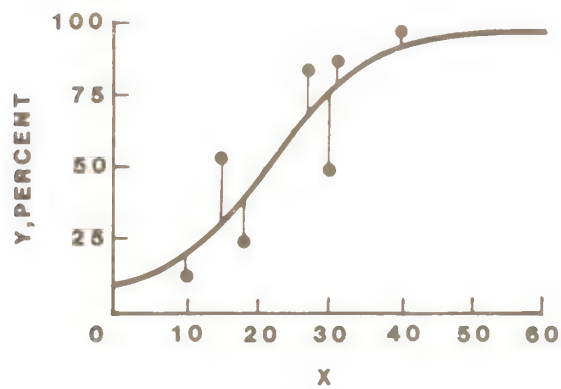

Figure 2.—A graphed estimate of the true form of the relation between X and Y.

The foregoing procedures apply to any curve shape in any quadrant or combinations of quadrants. They also apply to two-dimensional segments within three-dimensional relations.

GRAPHIC HYPOTHESIS DEVELOPMENT - THREE DIMENSIONS

Extension of two-dimensional procedures to a three-dimensional case is shown in figure 3.

Note that $X1$ and $X2$ are invariably correlated to a greater or lesser extent so that estimates of the $X1$ effect will generally improve with a reduction in breadth of the $X2$ segments. While only three $X2$ segments are shown in figure 3 for the sake of simplicity, five or more segments would have been more desirable if more data points had been available. The same procedure applies to additional independent variables, such as $X3$ in figure 4 (following).

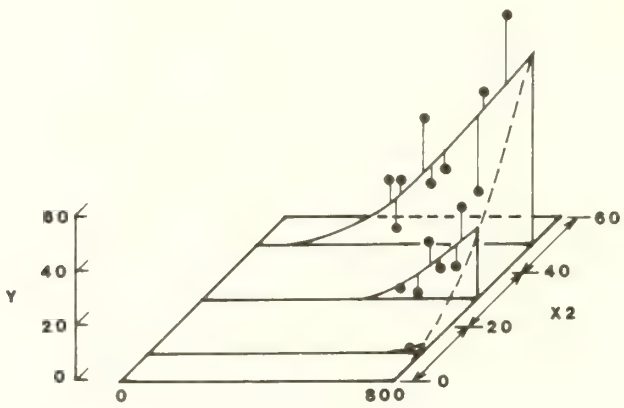

Figure 3.—A graphed estimate of the true form of the relation developed over X1 within each of three segments of the range in X2.

GRAPHIC HYPOTHESIS DEVELOPMENT - FOUR OR MORE DIMENSIONS

Extension of three-dimensional procedures to a four-dimensional case is shown in figure 4. The same procedures can be extended to five or more dimensions.

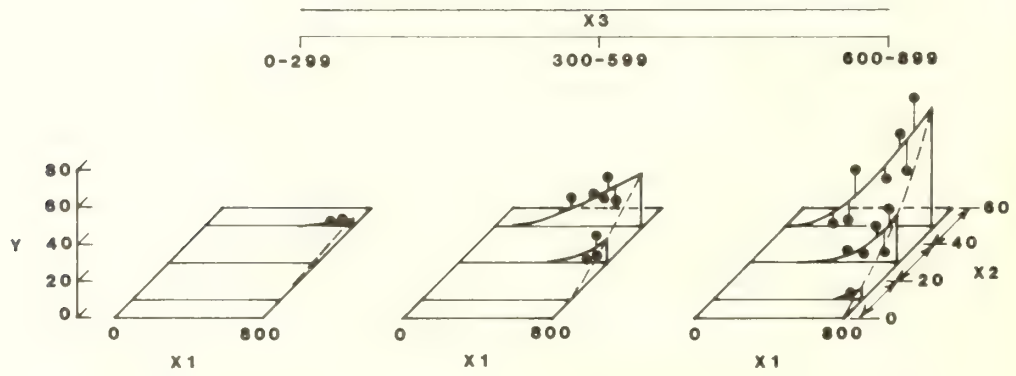

Figure 4.—A graphed estimate of the true form of the relation developed over X1 for three segments of the range in X2 within each of three segments in the range of X3.

MATHEMATICAL DESCRIPTIONS OF GRAPHED HYPOTHESES - TWO DIMENSIONS

Regardless of the number of dimensions and complexity of the relation to be described, it is ultimately sorted into two-dimensional effects that are described individually. These are finally reassembled, additively or multiplicatively as appropriate, to arrive at the whole descriptor.

Each two-dimensional element is described with either one or both of two families of curves, X^n, $n \geq 1$, or e^{-k}, a three-parameter sigmoidal function designed for easy use by the modeler.

Outline for "TWO DIMENSIONS"

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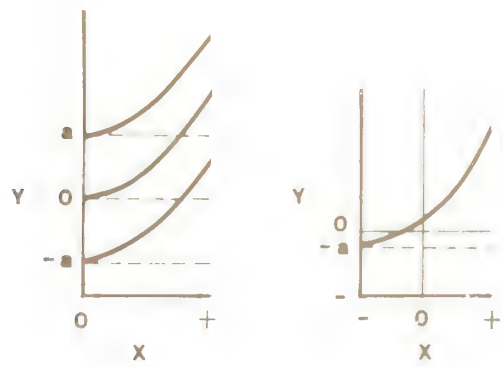
Class X^n, $n \geq 1$ (Exponential Curves) 10

Curves flat- to concave-upward, positive slope:

In the right half of two-space (example 1) 10

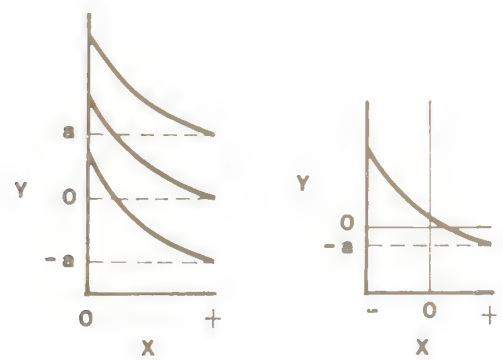
without constraint in two-space (example 2) 14



Curves flat- to concave-upward, negative slope:

In the right half of two-space (example 3) 15

without constraint in two-space (example 4) 16



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Curves flat- to convex-upward, positive slope:
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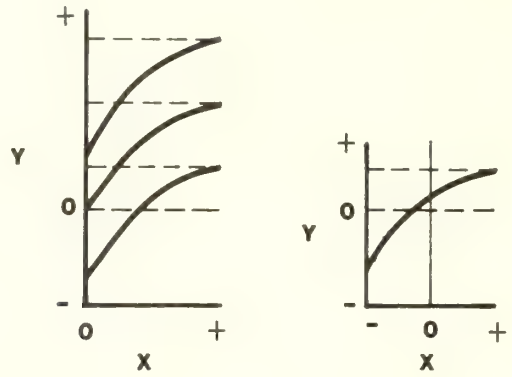

Curves flat- to convex-upward, negative slope:
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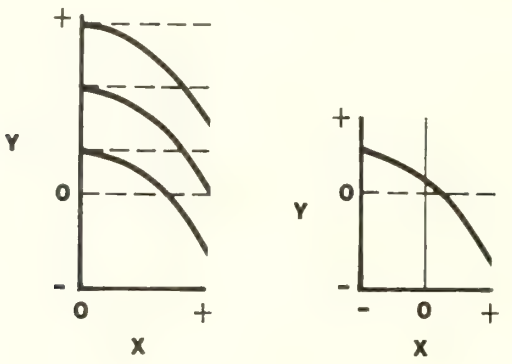
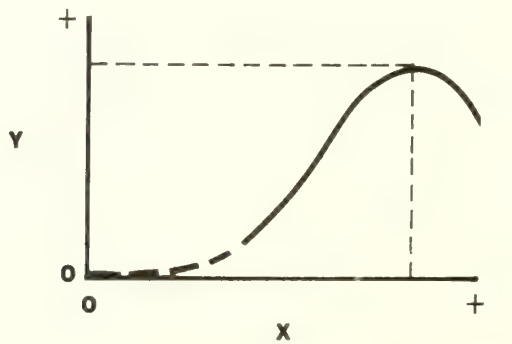


Class e^{-K} *(Bell-Shaped or Sigmoidal Curves)* 21
The implied curve fully expressable in the
upper-right quadrant of two-space 21



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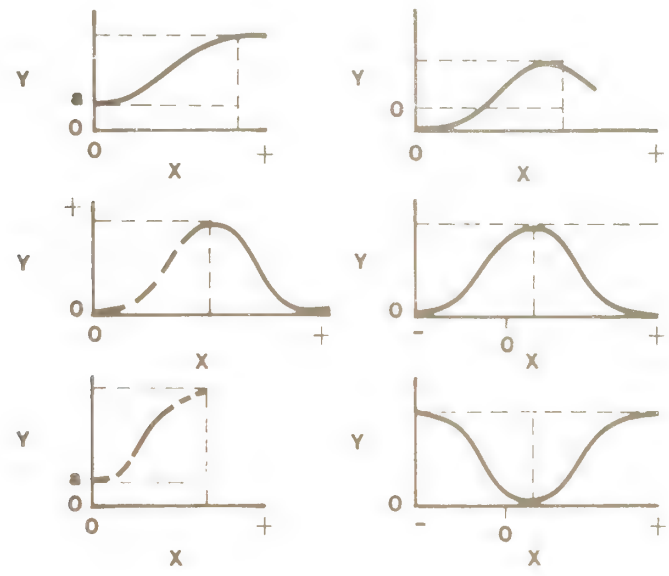
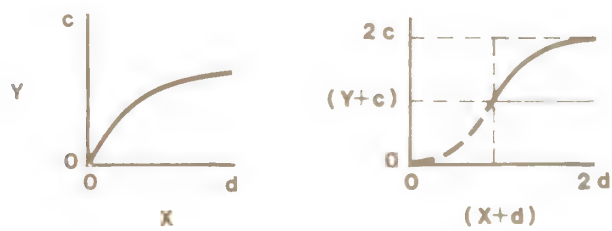
Alternative Arrangements in Space 25



Using Applicable Parts of e^{-h} *Curves* 28



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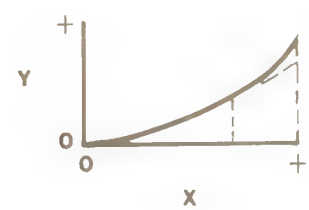

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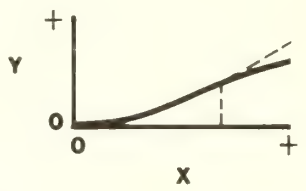
Two-Component X^n, *with Inflection* 33



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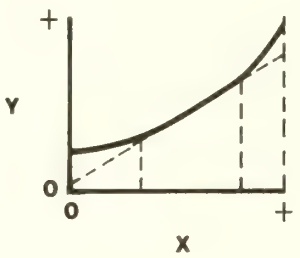
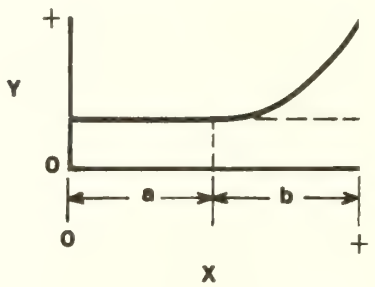
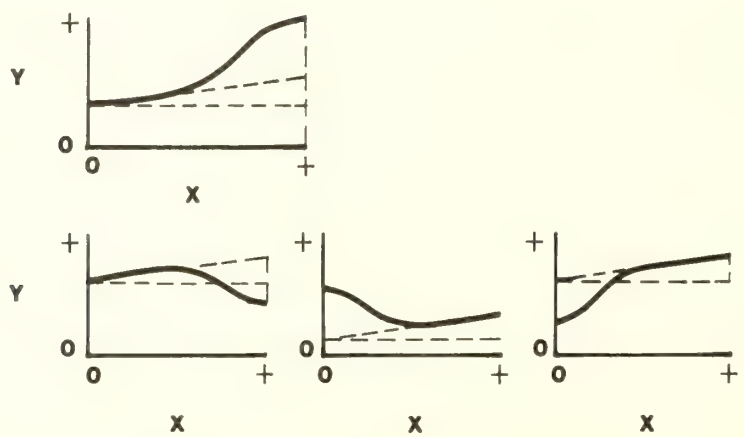


Segmentation with X^n 34



Straight-Line Slopes (X^n, $n = 1$) Plus or Minus Sigmoids 35



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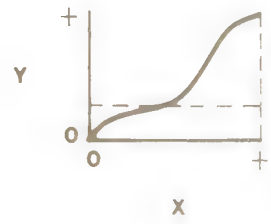
X^n, $n > 1$, Plus Sigmoids 36



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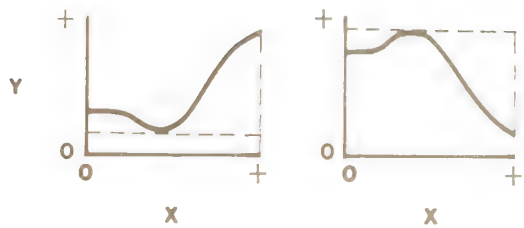
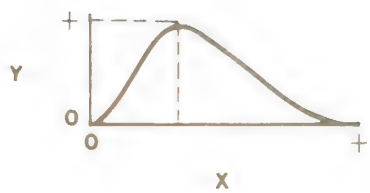
Unsegmented 36



Segmented 37



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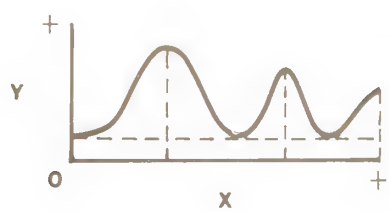


Class-X^n, $n \geq 1$, (Exponential Curves)

Reference is made to Matchacurve-2 (Jensen and Homeyer 1971) in which use of X^n covers not only $n \geq 1$, but $0 < n \leq 1$ and $n < 0$ as well. Our experience since that work was published has indicated that almost all descriptor needs involving X^n are reasonably well met with the ($n \geq 1$) option; so methods and Standards in this summary publication include the ($n \geq 1$) option only, a great simplification over the Matchacurve-2 presentation (Jensen and Homeyer, 1971).

Descriptor development for graphed hypotheses accommodates all possible orientations in the upper-right quadrant of two-dimensional space (fig. 5), and those involving any combination of these up to four quadrants.

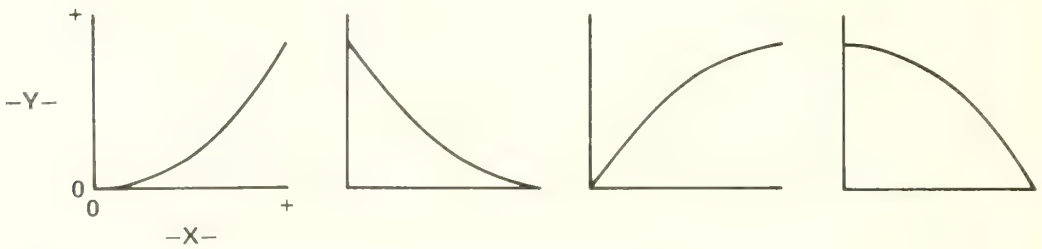


Figure 5.—Alternative orientations of X^n-curves in the upper-right quadrant.

Regardless of the form alternative or quadrant(s) involved, the X-axis can be altered as needed to orient the curve in the upper-right quadrant and through the origin. The analyst simply compares a normalized-scale version of this reoriented hypothesis with graphed standard curves, or Standards (appendix, marked for cut-out), and selects the two adjacent ones most nearly like his own in shape. Interpolation between the curves and their associated powers (n) results in identification of the best alternative offered by the system.

Note that if duplicates are made of the standards, the copies should be **exactly** the same scale as the Standards.

Example 1

Here (fig. 6), the hypothesis is a flat- to concave-upward, positive slope, and occupying any vertical position in the right half of two-dimensional space. Mathematical formulation for the middle alternative (zero Y-intercept) is detailed in figure 7 and in table 1, but the methods will accommodate any Y-intercept.

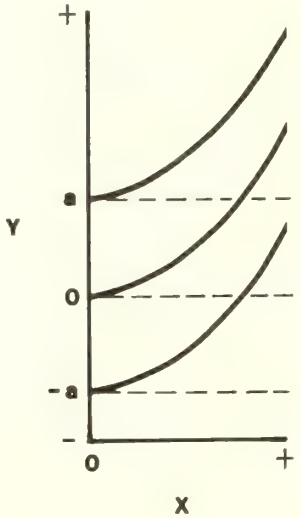


Figure 6.—$Y = a + bX^n$, $0 \leq X \leq XP$, $n \geq 1$.

In figure 7, the analyst visually estimates the curve form expressed in the data and simultaneously draws and hand-fits the form to the data by approximate least deviations. All of this is accomplished within the constraints of expectation. Mathematical formulation procedures follow in table 1.

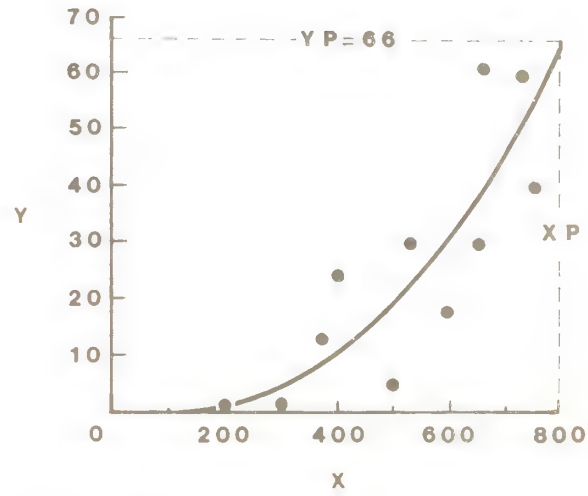


Figure 7.—$Y = 0 + bX^n$.
$0 \leq X \leq XP, n \geq 1$.

Table 1.—Mathematical hypothesis development

Control points		X	$(Y - a)$	Overlay control points		$b(X1)^{2.70}$	Performance of Y1	$b(X1)^{2.64}$	Performance of Y2	$a + Y2$
X (1)	Y (2)	$X1$ (3)	$Y1$ (4)	$XP1$ (5)	$Y1/YP1$ (6)	$Y1$ (7)	$(Y1 - Y1)$ (8)	$Y2$ (9)	$(Y2 - Y1)$ (10)	Y (11)
0	0.0	0	0.0	0.00	0.00	0.0	0.0	0.0	0.0	0.0
200	1.3	200	1.3	.25	.02	1.6	+ .3	1.7	+ .4	1.7
400	10.6	400	10.6	50	16	10.2	− .4	10.6	.0	10.6
600	31.4	600	31.4	.75	.48	30.4	− 1.0	30.9	− .5	30.9
800	66.0	800	66.0	1.00	1.00	66.0	.0	66.0	0	66.0

• Columns 1 and 2: Select representative control points (point coordinates) from the graphed hypothesis, including XP, the largest value of X to be represented by the hypothesis (800, in this case), and YP, the corresponding smoothed value of Y (66 here). Five control points have been selected and are listed in these columns, along with computations necessary to the search for a suitably similar mathematical curve-form. Use fewer control points where the desired sensitivity is less; use more for greater sensitivity.

• Column 3: The X-scale remains unchanged, but is relabeled as $X1$ for consistency with procedures for subsequent, more complex examples. XP is called $XP1$ in the $X1$-scale.

• Column 4: Subtract the intercept, a, from all control point Y-values to produce $Y1$. Whether a is zero (as here) or any positive or negative value, $Y1$-values will have zero intercept and will be in the upper-right quadrant of two-dimensional space. Such orientation of the curve is necessary to use of the Standards. YP is called $YP1$ in the $Y1$-scale.

• Columns 5 and 6: Compute ratios of $X1$ and $Y1$ to $XP1$ and $YP1$, respectively. These arrays of ratios are the normalized (proportional) scales for the $X1$ and $Y1$ control points. The resulting overlay points can now be plotted on a sheet of conventional graph paper (10 × 10 to ½ inch is best), at the exact scale specified in figure 8. Although not necessary, it may help to draw a smooth curve through the points. Call this the overlay curve. It is the normalized version of the original hypothesis plotted at the same scale used for the Standards (fig. 8).

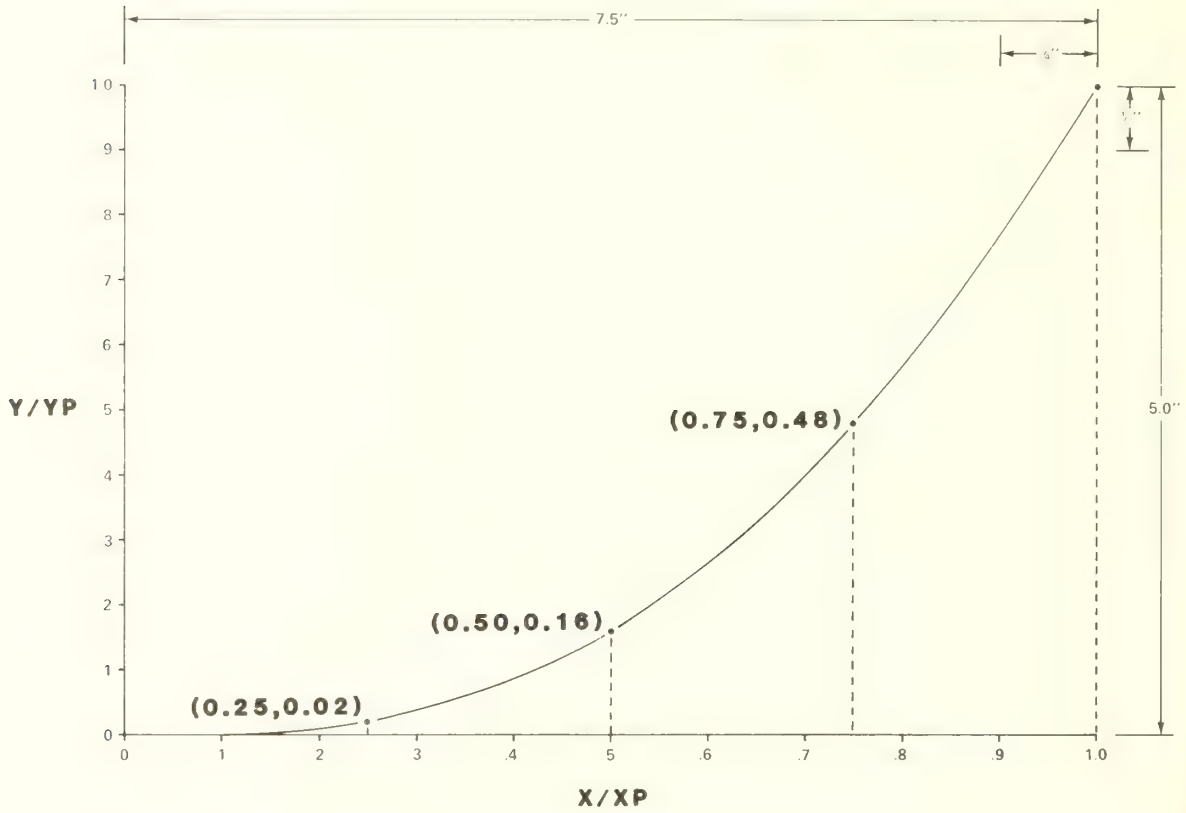


Figure 8.—Here the graphed curve has been normalized and plotted at the same scale as the Standards.

• Place the overlay graph over the Standards, being certain that the X- and Y-axes are matched exactly. Find the Standards that most nearly bracket the overlay curve (fig. 9). In this case, $n = 2.5$ and 3.0 bracket the overlay curve nicely. Note that a light source behind the graphs that are being compared will assist in the matching process. Where the hypothesized curve is not suitably matched by the Standards, a segmented or multicomponent X^n-function, or some portion of a sigmoid may suffice (see Contents).

Use proportional departure of the overlay curve from the left bracketing Standard to approximate an interpolated value between $n = 2.5$ and 3.0. This is best done at a point where curve-form accuracy is most crucial—the point of sharpest bend was adopted in this case. From figure 9, the interpolated n is 2.7.

• Column 7: After the analyst has made the first approximation of the mathematical form of the hypothesis, $Y1 = b(X1)^{2.70}$, where $b = YP1/(XP1)^{2.70} = 66/(800)^{2.70} = 9.576 \times 10^{-7}$, he can make associated estimates, $\hat{Y}1$, at each control point $X1$ value as shown.

• Column 8: Differences between estimated and original $Y1$ values indicate that $b(X1)^{2.70}$ has a preponderance of negative departures (that is, too much curvature). Try flatter curves (less power) iteratively.

Figure 9.—The Standards best matched to the original curve bracket the overlay curve.

• Column 9: A second estimator, $Y2 = b(X1)^{n}$, where $b = YP1(XP1)^{2.64} = 1.430 \times 10^{-6}$, produces $Y2$ values as shown.

• Column 10: Differences between estimated $Y2$ and original $Y1$ values are small and well balanced (+ and −); so $b(X1)^{2.64}$ is adopted.

• Column 11: The final hypothesis is then, $Y = a + bX^{n} = 0 + 1.430 \times 10^{-6}(X1)^{2.64}$, or, since $X = X1$, $Y = 1.430 \times 10^{-6}(X)^{2.64}$.

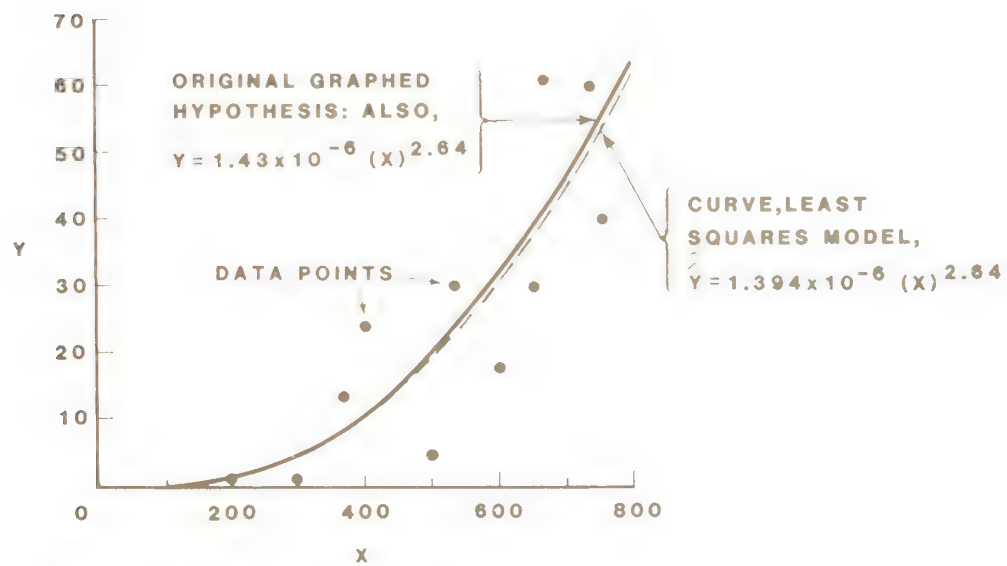


Figure 10.—The fitted model has been plotted over the original graphed form.

Note that at the scale shown in figure 10, differences between the graphed hypothesis and $Y = 1.430 \times 10^{-6}(X)^{2.64}$ are barely discernible. This example produced a closer mathematical match for the objective curve than one might expect on the average, but serves to demonstrate the procedures very well.

• As a matter of fitting-methods interest, the hypothesis was then fitted by least squares (forced through the origin) back to the data from which it was partially derived

and: $\hat{\hat{Y}} = c(XT)$, where $XT = b(X1)^n$

$c = \Sigma(XT^*Y)/\Sigma(XT)^2 = 0.9748$

or: $\hat{\hat{Y}} = 1.394 \times 10^{-6}(X)^{2.64}$ and is plotted in figure 10 as a dashed line.

The least squares model is quite close to the graphed hypothesis as might be expected, but the mathematical hypothesis should not be evaluated statistically on this used half of the data set. Rather, the same fitting procedures can be applied to the unused half of the data set and, for this, conventional statistical evaluations are appropriate.

• Given the same general hypothesis, $Y = a + 1.430 \times 10^{-6}(X)^{2.64}$, but with a being a **fixed constraint** other than zero, the fitting process is identical to that just specified. Assuming for example that a is fixed at -20, the final form would be $\hat{\hat{Y}} = -20 + 1.394 \times 10^{-6}(X)^{2.64}$, $0 \leq X \leq 800$.

• Where a is *variable* (not fixed), linear curve-fitting techniques can be used to estimate both a and b in $Y = a + b(X1)^n$. Then, letting $X = (X1)^n$, $b = \Sigma xy/\Sigma x^2$ and $a = \bar{Y} - b\bar{X}$, as in conventional notation.

Example 2

Assume a graphed hypothesis like that in figure 11 (flat- to concave-upward, positive slope, with negative Y-intercept, a, and crossing into the left half of two-dimensional space). Mathematical formulation procedures follow closely those of example 1 and are summarized in table 2.

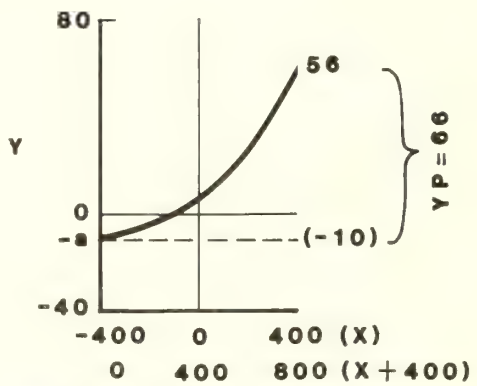


Figure 11.—$Y = a + b(X - k)^n$, $k \leq X \leq XP$, $n \geq 1$.

Table 2.—Mathematical hypothesis development

Control points		$(X-k)$ =	$(Y-a)$ =	Overlay control points		$b(X1)^{2.70}$ =	Performance of Y1	$b(X1)^{2.64}$ =	Performance of Y2	$a + \hat{Y}2$ =
X (1)	Y (2)	X1 (3)	Y1 (4)	X1/XP1 (5)	Y1/YP1 (6)	Y1 (7)	$(\hat{Y}1 - Y1)$ (8)	$\hat{Y}2$ (9)	$(\hat{Y}2 - Y1)$ (10)	$\hat{Y}$ (11)
−400	−10.0	0	0.0	0.00	0.00	0.0	0.0	0.0	0.0	−10.0
−200	− 8.7	200	1.3	.25	.02	1.6	+ .3	1.7	+ .4	− 8.3
0	.6	400	10.6	.50	.16	10.2	− .4	10.6	.0	.6
200	21.4	600	31.4	.75	.48	30.4	−1.0	30.9	− .5	20.9
400	56.0	800	66.0	1.00	1.00	66.0	.0	66.0	.0	56.0

- Columns 1 and 2: List control points representative of the curve.
- Shift the curve to the upper-right quadrant to match the position of the Standards:
  Column 3: Let $X1 = (X - k)$, where k = the smallest value of X to be represented by the equation (-400 here). Then, $X1 = (X - [-400]) = (X + 400)$, and $XP1 = 800$.
  Column 4: $Y1 = (Y - a) = (Y - [-10]) = (Y + 10)$, and $YP1 = 66.0$.
- Columns 5–10: Identical to example 1, table 2, columns 5–10.
- Column 11: The final hypothesis is then, $Y = a + bX^n = -10 + 1.430X10^{-6}(X + 400)^{2.64}$, $-400 \leq X \leq 400$.
- Least squares fit.
  With a fixed; $Y = c(XT)$, where $XT = b(X1)^n$, $c = \Sigma(XT * Y1)/(\Sigma XT)^2$, and $\hat{Y} = a + c(b(X1)^n)$. In this case, $\hat{Y} = -10 + c(b[X1]^n)$.
  With a variable, $\hat{Y} = a + b(X1)^n$. Letting $X = (X1)^n$ and, under conventional notation, $b = \Sigma xy/\Sigma x^2$ and $a = \bar{Y} - b\bar{X}$.

Example 3

Assume a hypothesis like that in figure 12 (flat- to concave-upward, negative slope, and occupying any vertical position in the right half of two-dimensional space). Mathematical formulation for the middle alternative (a = zero) is detailed in table 3, but the methods will accommodate any a value. Procedures follow closely those of example 1.

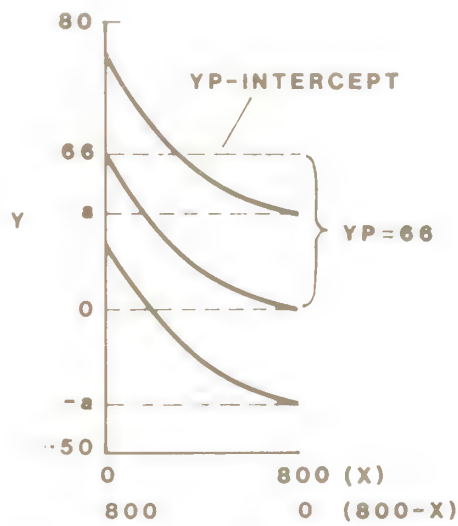


Figure 12.—$Y = a + b(XP - X)^n$. $0 \leq X < XP$, $n \geq 1$.

Table 3.—Mathematical hypothesis development

Control points		$(XP - X)$ =	$(Y - a)$ =	Overlay control points		$b(X1)^{2.70}$ =	Performance of Y1	$b(X1)^{2.64}$ =	Performance of Y2	$a + Y2$ =
X (1)	Y (2)	X1 (3)	Y1 (4)	X1/XP1 (5)	Y1/YP1 (6)	Y1 (7)	(Y1 – Y1) (8)	Y2 (9)	(Y2 – Y1) (10)	Y (11)
0	66.0	800	66.0	1.00	1.00	66.0	0 0	66.0	0.0	66.0
200	31.4	600	31.4	75	.48	30.4	– 1.0	30.9	– .5	30.9
400	10.6	400	10.6	.50	16	10.2	– .4	10.6	.0	10.6
600	1.3	200	1.3	25	.02	1.6	+ .3	1.7	+ .4	1.7
800	0	0	0	.00	.00	.0	.0	.0	.0	.0

- Columns 1 and 2: List control points representative of the curve.
- Shift the curve to the upper-right quadrant to match the position of the Standards:
  Column 3: Let $X1 = (XP - X) = (800 - X)$, and $XP1 = 800$.
  Column 4: Since a = zero here, $Y1 = (Y - a) = (Y - 0) = Y$, and $UP1 = 66.0$.
- Columns 5–10: Identical to example 1, table 2, columns 5–10.
- Column 11: The final hypothesis is then,
  $\hat{\hat{Y}} = a + b(XP - X)^n = 0 + 0.1430 \times 10^{-6}(800 - X)^{2.64}$, $0 \leq X \leq 800$.
- Least squares fit.
  With a fixed at any value; $\hat{\hat{Y}} = c(XT)$, where $XT = b(X1)^n$, $c = \Sigma)XT * Y1)/(\Sigma XT)^2$, and $\hat{\hat{Y}} = a + c(b(X1)^n)$.
  With a variable; $\hat{\hat{Y}} = a + b(X1)^n$. Letting $X = (X1)^n$ and, under conventional notation, $b = \Sigma xy/\Sigma x^2$ and $a = \bar{Y} - b\bar{X}$.

Example 4

Assume a hypothesis like that in figure 13 (flat- to concave-upward, negative slope, with negative Y-intercept, a, and crossing into the left half of two-dimensional space). Mathematical formulation procedures follow closely, those of example 1 and are summarized in table 4.

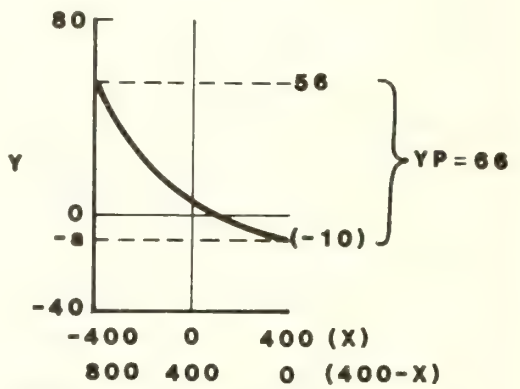


Figure 13.—$Y = a + (XP - X)^n$, $k \leq X \leq XP$, $n \geq 1$.

Table 4.—Mathematical hypothesis development

Control points		$(XP - X)$ =	$(Y - a)$ =	Overlay control points		$b(X1)^{2.70}$ =	Performance of Y1	$b(X1)^{2.64}$ =	Performance of Y2	$a + \hat{Y}2$ =
X	Y	X1	Y1	X1/XP1	Y1/YP1	$\hat{Y}1$	$(\hat{Y}1 - Y1)$	$\hat{Y}2$	$(\hat{Y}2 - Y1)$	$\hat{Y}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
−400	56.0	800	66.0	1.00	1.00	66.0	0.0	66.0	0.0	56.0
−200	21.4	600	31.4	.75	.48	30.4	−1.0	30.9	− .5	20.9
0	.6	400	10.6	.50	.16	10.2	− .4	10.6	.0	.6
200	− 8.7	200	1.3	.25	.02	1.6	+ .3	1.7	+ .4	− 8.3
400	−10.0	0	.0	.00	.00	.0	.0	.0	.0	−10.0

- Columns 1 and 2: List control points representative of the curve.
- Shift the curve to the upper-right quadrant to match the position of the Standards:
  Column 3: Let $X1 = (XP - X) = (400 - X)$, and $XP1 = 800$.
  Column 4: Let $Y1 = (Y - a) = (Y - (-10)) = (Y + 10)$, and $YP1 = 66.0$.
- Columns 5–10: Identical to example 1, table 2, columns 5–10.
- Column 11: The final hypothesis is then,
  $\hat{Y} = a + b(XP - X)^n = -10 + 1.430 \times 10^{-6}(400 - X)^{2.64}$, $k \leq X \leq 400$, and k = the lower applicable limit (-400 here) of the X-range.
- Least squares fit.
  With a fixed at any value; $\hat{Y} = c(XT)$,
  where $XT = b(X1)^n$, $c = \Sigma(XT * Y1)/(\Sigma XT)^2$, and $Y = a + c(b(X1)^n)$.
  With a variable, $\hat{Y} = a + b(X1)^n$. Letting $X = (X1)^n$ and, under conventional notation, $b = \Sigma xy/\Sigma x^2$ and $a = Y - bX$.

Example 5

Assume a hypothesis like that in figure 14 (flat- to convex-upward, positive slope, and occupying any vertical position in the right half of two-dimensional space). Mathematical formulation for the middle alternative is detailed in table 5. Procedures follow closely those of example 1.

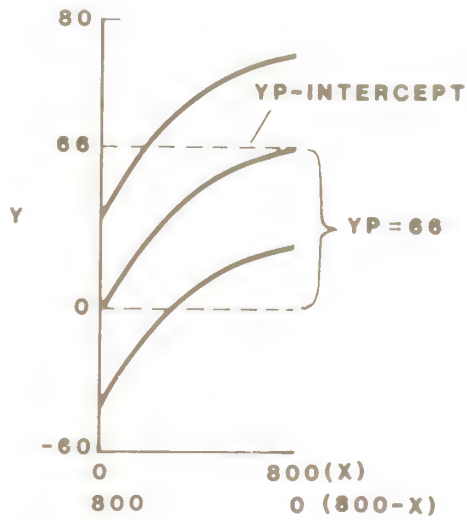


Figure 14.—$Y = YP - b(XP - X)^n$, $0 \cdot X \cdot XP, n \cdot 1$.

Table 5.—Mathematical hypothesis development

Control points		$(XP - X)$ $(YP - Y)$		Overlay control points		$b(X1)^{2.70}$	Performance of Y1	$b(X1)^{2.64}$	Performance of Y2	a + Y2 =
X	Y	X1	Y1	X1/XP1	Y1/YP1	Y1	(Y1 – Y1)	Y2	(Y2 – Y1)	Y
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
0	0.0	800	66.0	1.00	1.00	66.0	0.0	66.0	0.0	0.0
200	34.6	600	31.4	75	48	30.4	– 1.0	30.9	– .5	35.1
400	55.4	400	10.6	50	16	10.2	– .4	10.6	.0	55.4
600	64.7	200	1.3	25	02	1.6	+ .3	1.7	+ .4	64.3
800	66.0	0	0	00	00	.0	.0	0	.0	66.0

- Columns 1 and 2: List control points representative of the curve.
- Shift the curve to the upper-right quadrant to match the position of the Standards:
  Column 3: Let $X1 = (XP - X) = (800 - X)$, and $XP1 = 800$.
  Column 4: Let $Y1 = (YP - Y) = (66.0 - Y)$, and $YP1 = 66.0$.
- Columns 5–10: Identical to example 1, table 2, columns 5–10.
- Column 11: The final hypothesis is then,
  $\hat{Y} = YP - b(XP - X)^n = 66.0 - 1.430 \times 10^{-6}(800 - X)^{2.64}$, $0 \leq X \leq 800$.
- Least squares fit.
  With YP fixed at any value; $\hat{\hat{Y}} = c(XT)$, where $XT = b(X1)^n$, $c = (XT * Y1)/(XT)^2$, and $\hat{\hat{Y}} = YP - c(b(X1)^n)$.
  With YP variable, $\hat{\hat{Y}} = a + b(X1)^n$. Letting $X = (X1)^n$ and, under conventional notation, $b = \Sigma xy/\Sigma x^2$ and $a = \bar{Y} - b\bar{X}$.

Example 6

Assume a hypothesis like that in figure 15 (flat- to convex-upward, positive slope with negative Y-intercept, and crossing into the left half of two-dimensional space). Mathematical formulation for this curve is detailed in table 6. Procedures closely follow those of example 1.

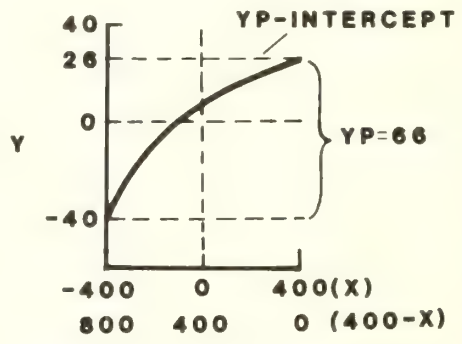


Figure 15.—$Y = YP - (XP)^n$, $k \leq X \leq XP$, $n \geq 1$.

Table 6.—Mathematical hypothesis development

Control points		$(XP - X)$ =	$(YP - Y)$ =	Overlay control points		$b(X1)^{2.70}$ =	Performance of Y1	$b(X1)^{2.64}$ =	Performance of Y2	$a + Y2$ =
X (1)	Y (2)	$X1$ (3)	$Y1$ (4)	$X1/XP1$ (5)	$Y1/YP1$ (6)	$\hat{Y}1$ (7)	$(\hat{Y}1 - Y1)$ (8)	$\hat{Y}2$ (9)	$(\hat{Y}2 - Y1)$ (10)	$\hat{Y}$ (11)
−400	−40.0	800	66.0	1.00	1.00	66.0	0.0	66.0	0.0	−40.0
−200	− 5.4	600	31.4	.75	.48	30.4	− 1.0	30.9	− .5	− 4.9
0	15.4	400	10.6	.50	.16	10.2	− .4	10.6	.0	15.4
200	24.7	200	1.3	.25	.02	1.6	+ .3	1.7	+ .4	24.3
400	26.0	0	.0	.00	.00	.0	.0	.0	.0	26.0

- Columns 1 and 2: List control points representative of the curve.
- Shift the curve to the upper-right quadrant to match the position of the Standards:
  Column 3: Let $X1 = (XP - X) = (400 - X)$ and $XP1 = 800$.
  Column 4: Let $Y1 = (YP - Y) = (66.0 - Y)$ and $YP1 = 66.0$.
- Columns 5–10: Identical to example 1, table 2, columns 5–10.
- Column 11: The final hypothesis is then,
  $\hat{Y} = YP - b(XP - X)^n = 66.0 - 1.430 \times 10^{-6}(400 - X)^{2.64}, \quad -400 \leq X \leq 400.$
- Least squares fit.
  With YP fixed at any value; $\hat{Y} = c(XT)$, where $XT = b(X1)^n$, $c = \Sigma(XT * Y1)/\Sigma(XT)^2$, and $\hat{Y} = YP - c(b(X1)^n)$.
  With YP variable, $\hat{Y} = a + b(X1)^n$. Letting $X = (X1)^n$ and, under conventional notation, $b = \Sigma xy/\Sigma x^2$, and $a = \bar{Y} - b\bar{X}$.

Example 7

Assume a hypothesis like that in figure 16 (flat- to convex-upward, negative slope and occupying any vertical position in the right half of two-dimensional space). Mathematical formulation for the middle alternative is detailed in table 7. Procedures closely follow those of example 1.

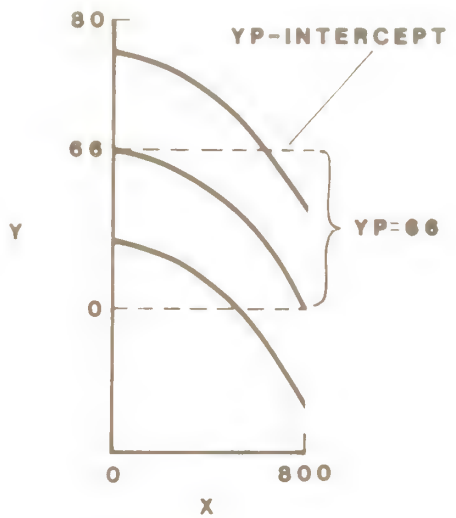


Figure 16.—$Y = YP - b(X)^n$, $0 \cdot X \cdot XP, n \cdot 1$.

Table 7.—Mathematical hypothesis development

Control points		X	$(YP - Y)$	Overlay control points		$b(X1)^{2.70}$	Performance of Y1	$b(X1)^{2.64}$	Performance of Y2	$a + Y2$
X	Y	$X1$	$Y1$	$X1/XP1$	$Y1/YP1$	$Y1$	$(Y1 - Y1)$	$Y2$	$(Y2 - Y1)$	Y
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
0	66.0	0	0.0	0.00	0.00	0.0	0.0	0.0	0.0	66.0
200	64.7	200	1.3	.25	.02	1.6	+ .3	1.7	+ .4	64.3
400	55.4	400	10.6	50	16	10.2	− .4	10.6	.0	55.4
600	34.6	600	31.4	75	48	30.4	− 1.0	30.9	− .5	35.1
800	.0	800	66.0	1.00	1.00	66.0	0	66.0	.0	.0

- Columns 1 and 2: List control points representative of the curve.
- Shift the curve to the upper-right quadrant to match the position of the Standards:
  Column 3: Let $X1 = X$, and $XP1 = 800$.
  Column 4: Let $Y1 = (YP - Y) = (66.0 - Y)$, and $YP1 = 66.0$.
- Columns 5–10: Identical to example 1, table 2, columns 5–10.
- Column 11: The final hypothesis is then,
  $\hat{Y} = YP - b(X)^n = 66.0 - 1.430 \times 10^{-6}(X)^{2.64}$, $0 \leq X \leq 800$.
  - Least squares fit.

  With YP fixed at any value; $\hat{\hat{Y}} = c(XT)$, where $XT = b(X1)^n$, $c = \Sigma(XT * Y1)/\Sigma(XT)^2$, and $\hat{\hat{Y}} = YP - c(b(X1)^n)$.

  With YP variable, $\hat{\hat{Y}} = a + b(X1)^n$. Letting $X = (X1)^n$ and, under conventional notation, $b = \Sigma xy/\Sigma x^2$, and $a = \bar{Y} - b\bar{X}$.

Example 8

Assume a hypothesis like that in figure 17 (flat- to convex-upward, negative slope with negative Y-intercept and crossing into the left half of two-dimensional space). Mathematical formulation for this curve is detailed in table 8. Procedures closely follow, those of example 1.

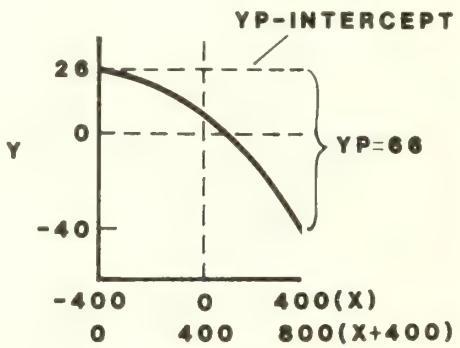


Figure 17.—$Y = YP - (X - k)^n$, $k \leq X \leq XP$, $n \geq 1$.

Table 8.—Mathematical hypothesis development

Control points		$(X - K)$ =	$(YP - Y)$ =	Overlay control points		$b(X1)^{2.70}$ =	Performance of $\hat{Y}1$	$b(X1)^{2.64}$ =	Performance of $\hat{Y}2$	$a + \hat{Y}2$ =
X (1)	Y (2)	$X1$ (3)	$Y1$ (4)	$X1/XP1$ (5)	$Y1/YP1$ (6)	$\hat{Y}1$ (7)	$(\hat{Y}1 - Y1)$ (8)	$\hat{Y}2$ (9)	$(\hat{Y}2 - Y1)$ (10)	$\hat{Y}$ (11)
−400	26.0	0	0.0	0.00	0.00	0.0	0.0	0.0	0.0	26.0
−200	24.7	200	1.3	.25	.02	1.6	+ .3	1.7	+ .4	24.3
0	15.4	400	10.6	.50	.16	10.2	− .4	10.6	.0	15.4
200	− 5.4	600	31.4	.75	.48	30.4	− 1.0	30.9	− .5	− 4.9
400	− 40.0	800	66.0	1.00	1.00	66.0	.0	66.0	.0	.0

- Columns 1 and 2: List control points representative of the curve.
- Shift the curve to the upper-right quadrant to match the position of the Standards:

Column 3: Let $X1 = (X - k)$, where k = the smallest value of X to be represented by the equation, -400 here. Then, $X1 = (X + 400)$, and $XP1 = 800$.
Column 4: Let $X1 = (YP - Y) = (26.0 - Y)$, and $YP1 = 66.0$.

- Columns 5–10: Identical to example 1, table 2, columns 5–10.
- Column 11: The final hypothesis is then,
  $Y = YP - b(X)^n = 26.0 - 1.430 \times 10^{-6}(X)^{2.64}$, $-400 \leq X \leq 400$.
- Least squares fit.
  With $\hat{YP}$ fixed at any value; $\hat{Y} = c(XT)$, where $XT = b(X1)^n$, $c = \Sigma(XT * Y1)/\Sigma(XT)^2$, and $\hat{Y} = YP - c(b(X1))^n$.
  With YP variable, $\hat{Y} = a + b(X1)^n$. Letting $X = (X1)^n$ and, under conventional notation, $b = \Sigma xy/\Sigma x^2$, and $a = \bar{Y} - b\bar{X}$.

Class e^{-K}, (Bell-Shaped or Sigmoidal Curves)

By reason of e^{-K} symmetry, shape parameters for this bell-shaped function are identical for either sigmoidal half (see e^{-K} ITS DERIVATION, CAPABILITIES, AND LIMITATIONS, appendix A). So, the e^{-K}-Standards are limited to sigmoids and these have normalized (proportional) X- and Y-scales, are in the upper right quadrant of two-dimensional space, and have zero intercept and slope upward to the right.

Representative control points (point-coordinates) are selected from a graphed sigmoidal hypothesis and these points are shifted to the position of the Standards through manipulation of the X- and Y-scales as needed. These revised scales are normalized (converted to proportions) and the normalized control points are plotted on graph paper at the exact scale of the Standards. This point-representation of the hypothesis (with or without the corresponding curve sketched in) can be laid over and compared with alternative sigmoids on any page of the Standards. When Standards are found that bracket the overlay curve and are suitably similar to it, the analyst can interpolate between parameters of these Standards to arrive at the best sigmoid provided by the system.

The result is a mathematical hypothesis that can be fitted to new data and evaluated statistically. For example, assume the graphed hypothesis shown in figure 18.

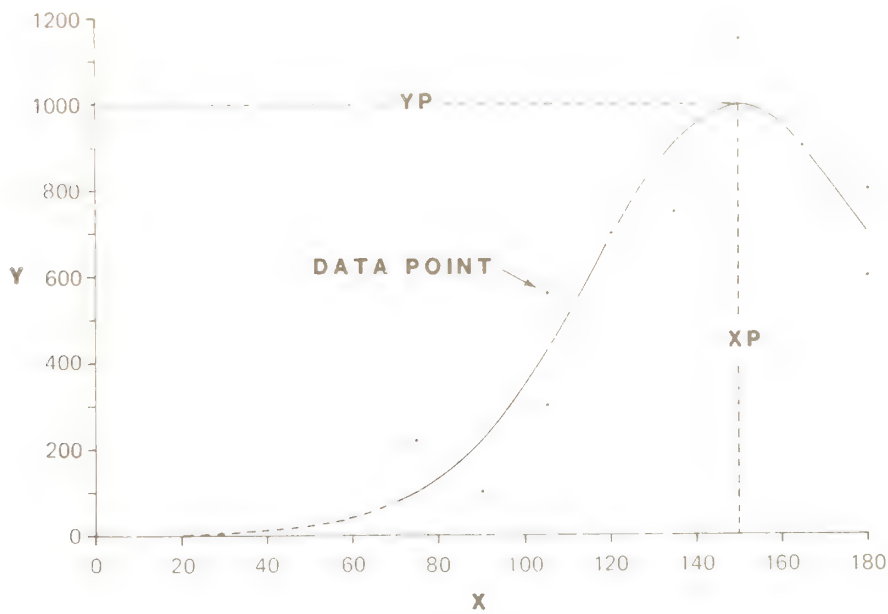


Figure 18.—Here, the expected curve form has been hand-fitted through plotted data points by approximate least deviations, (Karst 1958).

Recognizing that the shape of the curve on each side of the peak is about the same, it seems likely that a symmetrical curve fitting the left, most completely specified side of the relation, will also fit the top segment of the implied sigmoid to the right of the peak. So, we only need identify the mathematical form of the sigmoid to the left of the peak ($0 \leq X \leq 150$) to describe the entire graphed hypothesis. Mathematical formulation of this curve is detailed in table 9.

Table 9.—Mathematical hypothesis development

Control points		X =	$(Y-a)$ =	Overlay control points		$n=2, I=.67$ $XP1=150$, $YP1=1000$ $a=0, Y1=$	Performance of Y1	$n=2, I=.6701$ $XP1=150$, $YP1=1000$ $a=0, Y2=$	Performance of Y2
X (1)	Y (2)	$X1$ (3)	$Y1$ (4)	$X1/XP1$ (5)	$Y1/YP1$ (6)	$a+YP1*e^{-K}$ (7)	$(Y1-Y)$ (8)	$a+YP1*e^{-K}$ (9)	$(Y2-Y)$ (10)
0	0	0	0	0.00	0.00	0.0	0.0	0.0	0.0
75	100	75	100	.50	.10	100.6	+ .6	100.5	+ .5
105	430	105	430	.70	.43	437.5	+7.5	437.3	+7.3
120	700	120	700	.80	.70	692.6	−7.4	692.4	−7.6
150	1000	150	1000	1.00	1.00	1000.0	.0	1000.0	.0

Procedures generally follow those of example 1 for curves of the X^n-class.

- Columns 1 and 2: Five control points representative of the curve (including XP, the point in X at which Y peaks, and YP, the peak value of Y) have been selected from the sigmoid and are listed here. Use fewer control points where the desired sensitivity is less, more for greater sensitivity.
- Columns 3 and 4: The Standards for e^{-K} are oriented at zero in the upper-right quadrant (as for the X^n-Standards) and, since this curve already conforms, there are no transformations of the X- and Y-axes. So, $X1 = X$ and $Y1 = Y$, respectively. The $X1$- and $Y1$-variables will be shown and used here to be consistent with procedures for more complex examples that follow. Note that $XP1$ is the maximum value of $X1$ and that $YP1$ is the maximum value of $Y1$.
- Columns 5 and 6: Compute ratios of $X1$ and $Y1$ to $XP1$ and $YP1$, respectively. These arrays of ratios are the normalized (proportional) scales for the $X1$- and $Y1$-control points. The resulting overlay points can now be plotted on a sheet of conventional graph paper (10×10 to ½ inch is best), at the exact scale specified in figure 19 (5 inches for the YP range and ½ inch per 1/10 unit of $Y1$, 7½ inches for the XP range and 3/4 inch per 1/10 unit of $X1$). Although not necessary, it may help to sketch a smooth curve through these plotted points as shown in figure 19.
- Use this curve as an overlay for any page of the Standards, being careful to match exactly, the X- and Y-axes of the overlay with those of each page examined. Find adjoining sigmoids that are most nearly shaped like the overlay curve and bracket it (fig. 20).

Note in the Standards that I is the proportional distance of the inflection point from zero to 1.0 and n is the power of the negative exponents for e in e^{-K} (appendix). Curvature of the sigmoids becomes more pronounced with increased n, and n changes between

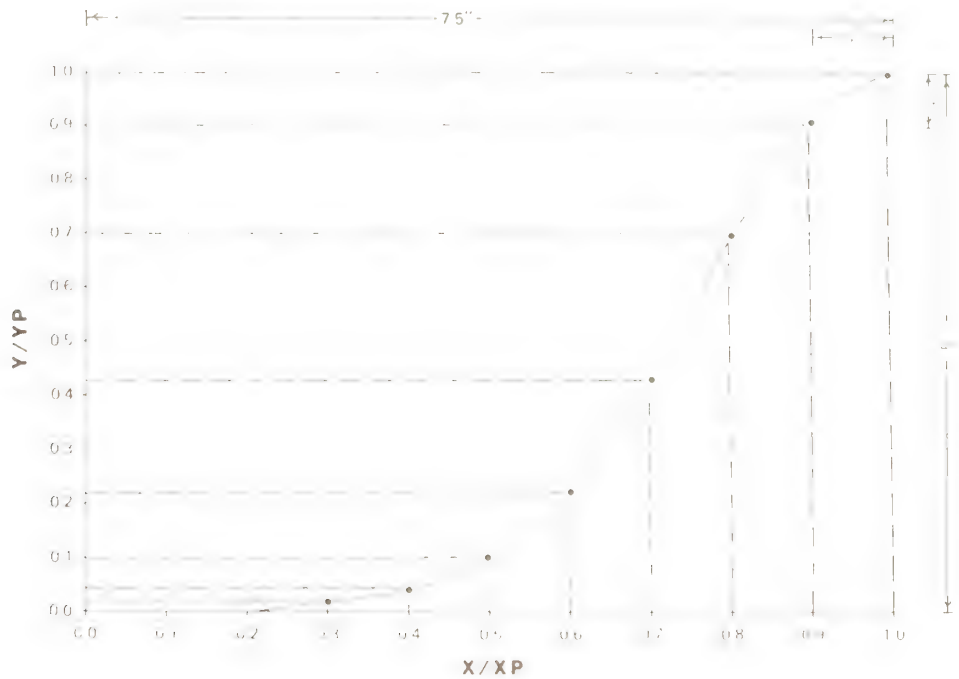


Figure 19.—The plotted overlay points.

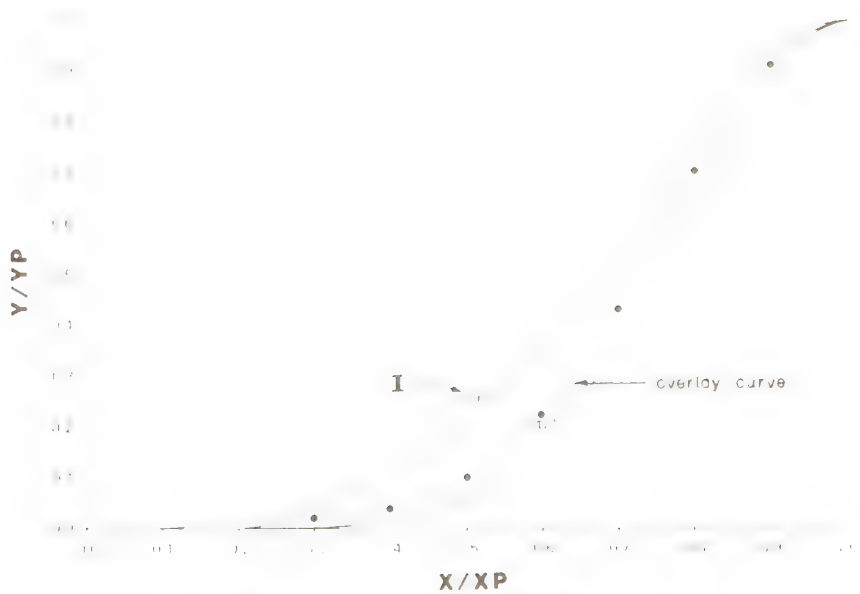


Figure 20.—The Standards of set ($n = 2$) are best matched to the original curve. Several adjoining curves of this set bracket the overlay curve.

pages of the Standards. There are nine sigmoids on each of the 10 graphs. In this case, the sigmoids $I = 0.6$ and 0.7 (fig. 20) bracket the overlay curve nicely.

Having found an acceptable pair of adjoining sigmoids that bracket the overlay curve, the analyst can interpolate between the proportional inflection points they represent and

thus select a sigmoid more nearly matching the hypothesis. Proportional horizontal departure of the overlay curve from the left bracketing sigmoid at $Y/YP1 = 0.5$ can be used as the basis for interpolation. In figure 20, the overlay curve lies at about the 70 percent point between inflection points 0.6 and 0.7; so the interpolated $I = 0.67$. (This same interpolating principle can also be used between Standards of different sets for refined "n" estimates as the need arises.) Then substituting in the parent e^{-K}-equation, we have:

$$e^{-K} = \left\{ \frac{e^{-\left|\frac{\frac{X}{XP} - 1}{1-I}\right|^{n}} - e^{-\left\{\frac{1}{1-I}\right\}^{n}}}{1 - e^{-\left\{\frac{1}{1-I}\right\}^{n}}} \right\} = \left\{ \frac{e^{-\left|\frac{\frac{X}{150} - 1}{.33}\right|^{2}} - e^{-\left\{\frac{1}{.33}\right\}^{2}}}{1 - e^{-\left\{\frac{1}{.33}\right\}^{2}}} \right\}$$

This is easily programed on a small desk-top computer (with the number of steps required generally being less than 100) and solved for $\hat{Y}1$-values at control-point $X1$-values.

- Column 7: e^{-K} (ranging only from 0 to 1) is scaled to the graphed hypothesis by simply multiplying e^{-K} by $YP1$ ($= YP$ here), the height of the sigmoid at its peak. Adding the intercept a, produces $\hat{Y}1$.
- Column 8: The selected sigmoid is reasonably close to that of the hypothesis with a slight surplus of positive values ($+0.6$), as shown. In the light of the Y-values involved (100, 430, 700), the departures $+0.6$, $+7.5$, and -7.4, respectively, are small and this sigmoid would most likely be adopted. But, as might be more appropriate in other cases, computer iteration can be used to select an even closer e^{-K}-approximation of the hypothesized sigmoid.
- Columns 9 and 10: $\hat{Y}2$ and its performance are slightly better at $I = 0.6701$. Assuming this to be the final form adopted, we have:

$$\hat{Y}2 = 0 + 1000 \left\{ \frac{e^{-\left|\frac{X}{150} - 1}{0.3299}\right|^{2}} - 0.001}{1 - 0.001} \right\}$$

And, since the right numerator is very small and the denominator approaches 1.0,

$$\hat{Y}2 = 0 + 1000 * e^{-\left|\frac{\frac{X}{150} - 1}{0.3299}\right|^{2}}, \text{ the final hypothesis.}$$

Note that at the scale shown in figure 21, differences between the graphed hypothesis and $\hat{Y}2$ are not discernible.

This example produced a closer mathematical match for the objective curve than one might expect on the average, but serves to demonstrate the procedures very well. As a

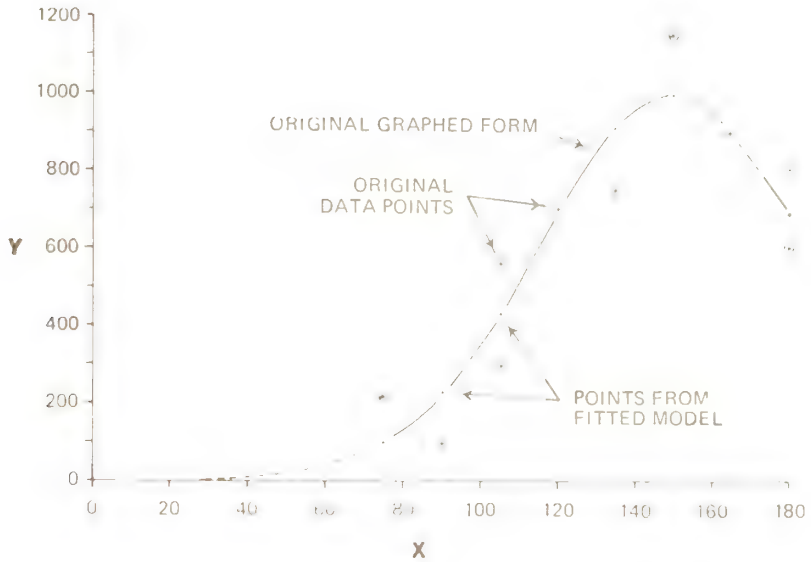


Figure 21.—Points from the fitted model have been plotted over the original graphed form.

matter of fitting methods interest, the hypothesis was then fitted by least squares (forced through the origin) back to the data from which it was partially derived.

And: $Y = cXT,\ XT = 1000 * e^{-\frac{X}{150}}$,

$c = (\Sigma(XT)) / \Sigma(XT)^2 = 0.9960$ or almost no change.

$$Y = 0.9960\left\{1000 * e^{-\frac{X}{150}}\right\},$$

which again, is not distinguishable from the hypothesis at the scale shown in figure 21.

While this result shows the development process has not deteriorated the fit of the hypothesis to the source data, statistical evaluation should be reserved for a new data set. The same fitting procedures are applicable.

Alternative Arrangements in Space

Unique spacial arrangement of the bell-shaped or sigmoidal form may necessitate adjustment of the *Y*-values for an intercept and/or manipulation of the *X*-scale to shift the objective figure to the upper right quadrant (like the Standards). Commonly encountered spacial alternatives and associated shifting techniques are shown in figures 22–26 which follow.

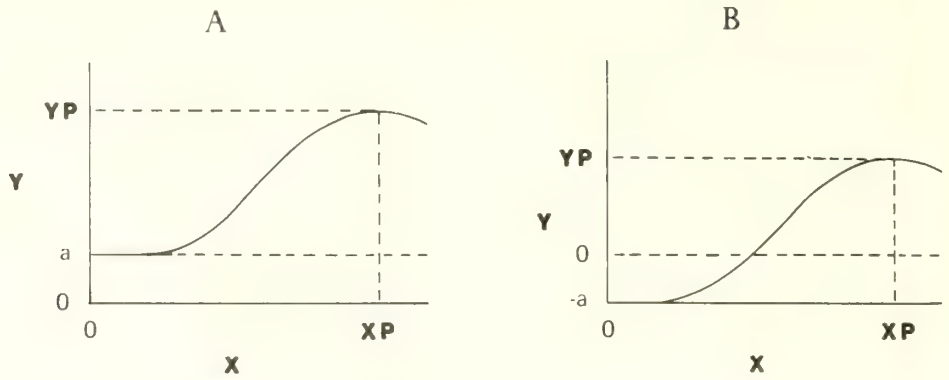


Figure 22.—Intercepts other than zero.

• Here, the sigmoid never drops below the intercept a, regardless of whether a is positive (fig. 22A) or negative (fig. 22B) and is suitably adjusted by (Y-a), as shown at the top of column 4, table 9.
Given the same hypothesis,

$\hat{Y} = 0 + 1000 * e^{-\left|\frac{\frac{X}{150} - 1}{0.3299}\right|^2}$, but with a being a constraint other than zero, the fitting process is identical to the one just specified. If, for example, the fixed $a = -20$, the final form would be:

$\hat{Y} = -20 + 0.9960(1000 * e^{-\left|\frac{\frac{X}{150} - 1}{0.3299}\right|^2}), \quad 0 \leq X \leq (2XP = 300).$

Where a is *variable* (not fixed), use linear curve-fitting techniques to estimate both a and b in

$$\hat{Y} = a + b(1000 * e^{-\left|\frac{\frac{X}{150} - 1}{0.3299}\right|^2}).$$

Then, letting $X = 1000 * e^{-K}$, as above, $b = \Sigma xy / \Sigma x^2$ and $a = \bar{Y} - b\bar{X}$, as in conventional notation.

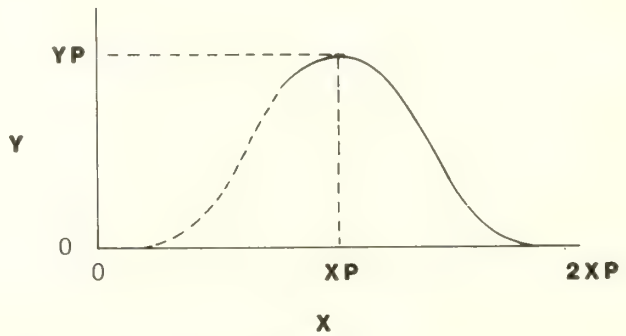


Figure 23.—Right half of implied bell-shaped curve specified.

• Plot the mirror image of the right side over the range $0 \leq X \leq XP$ and identify an appropriate sigmoid using X- and Y-values from that range, as in table 9. The sigmoid adopted will apply equally on either side of XP.

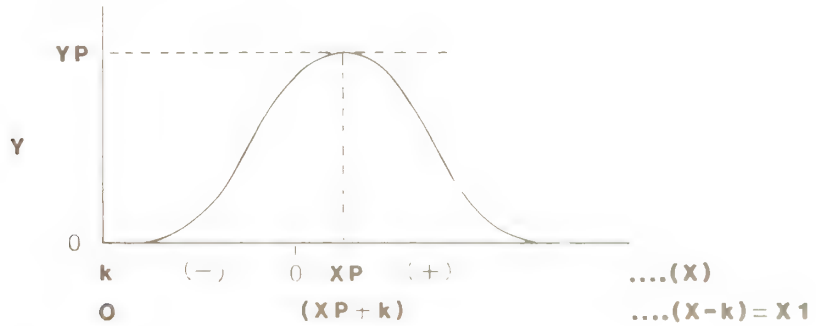


Figure 24.—X = 0 included in the range $XP \pm XP$.

• Substitute $X1 = (X - k)$ for X in the range $XP \leq X \leq (XP + k)$. Then follow table 9 procedures to identify an e^{-k}-sigmoid for the left side of the bell-shaped curve (= right side by virtue of symmetry here.)

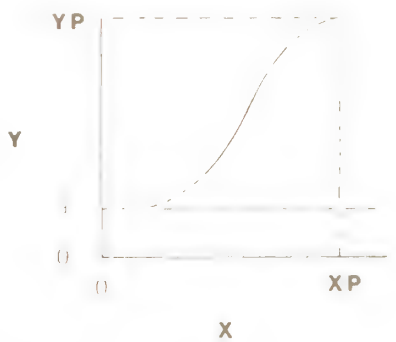


Figure 25.—Incomplete sigmoid specified.

• Complete the implied sigmoid in accord with expectation and identify e^{-K} as in table 9. The hypothesis would be presumed to apply in the range $0 \leq X \leq XP$.

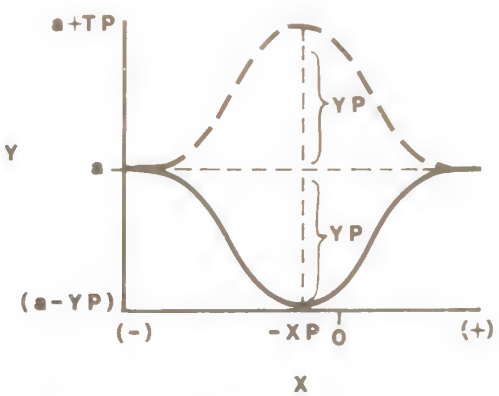


Figure 26.—Inverted bell-shaped curve, or portion thereof.

• Plot the negative departures of the curve from the intercept as positive departures on the intercept, that is, rotate the curve upward about a. Identify the appropriate sigmoid as shown previously and finally, $\hat{Y} = a - YP^{*}e^{-K}$

Using Applicable parts of e^{-K}-curves

On occasion, the added effort required to compile a multi-component descriptor can be avoided by utilizing a portion of a single-component curve.

Assume the curve in figure 27A is to be described mathematically and that no satisfactory matching curve has been found using X^n. As an alternative, the analyst could undertake a multiple-component description, but another single-component possibility exists.

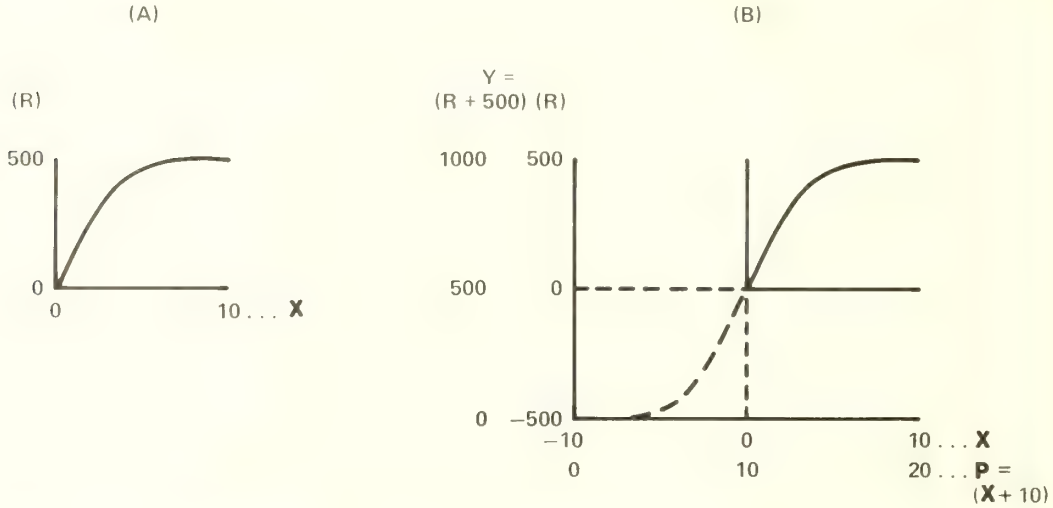


Figure 27.—Using the upper half of a sigmoid: (A) the problem, and (B) a solution.

• Extend the desired curve in figure 27A such that the resulting form approximates that of a sigmoid. Add a constant to the abscissa such that $XP \pm XP$ covers the pertinent range of X. $(X + 10)$ turns the trick here. Also, add a suitable constant, 500 in this case, to R to shift the entire sigmoid vertically to the upper-right quadrant. For representative points from the right half of this curve (for example, figure 27B), construct an overlay curve and find a matching Standard for the upper half of the overlay. The adopted single-component Standard fitted to the X- and Y-values then represents the original curve in the region $0 \leq X \leq 10$. The resulting descriptor is

$$Y = 1000^{*}e^{-K} - 500,\ 0 \leq X \leq 10,$$

or

$$Y = 1000 \left\{ \frac{e^{-\left| \frac{(X+10)}{20} - 1 \right|^{n}} - e^{-\left(\frac{1}{1-I}\right)^{n}}}{1 - e^{-\left(\frac{1}{1-I}\right)^{n}}} \right\}.$$

• Procedures for any fraction of any form are analogous.

Notes on $e^{\wedge}$

There may be cases where the $e^{\wedge}$-transform determined from the Standards is not sufficiently accurate for the purposes of the analyst. In such cases, curve-form description procedures beyond the scope of this paper must be used.

The portion of the curve to the right of XP is a mirror image of the left in $e^{\wedge}$. Once n and the proportional inflection point, I, have been selected and held constant, changes in Y values depend only on departure of X/XP from 1.0. Equal departures on opposite sides of 1.0 will result in equal Y-values. For the occasions when the analyst's curve is bell shaped and symmetrical, we really need only identify the $e^{\wedge}$-transform for one side (left), as for figure 18 and in table 9 procedures.

Every $e^{\wedge}$-transform is forced to zero at $X = 0$ and at $X = 2XP$ and should only be used within these limits (appendix, $e^{\wedge}$ DERIVATION).

Multiple-Component Descriptors

When a suitable match for a graphed two-dimensional hypothesis of the X^n-class cannot be found in the X^n-Standards, more satisfactory descriptors can often be developed by matching unique portions of the curve sequentially and adding descriptors for the parts to arrive at the whole. Also, development of descriptors for contiguous segments of the X-axis constitutes another flexible alternative.

One example, a commonly encountered kind of curve form that departs from the single-component Standards of the X^n-class, is represented by the graphed hypothesis in figure 28.

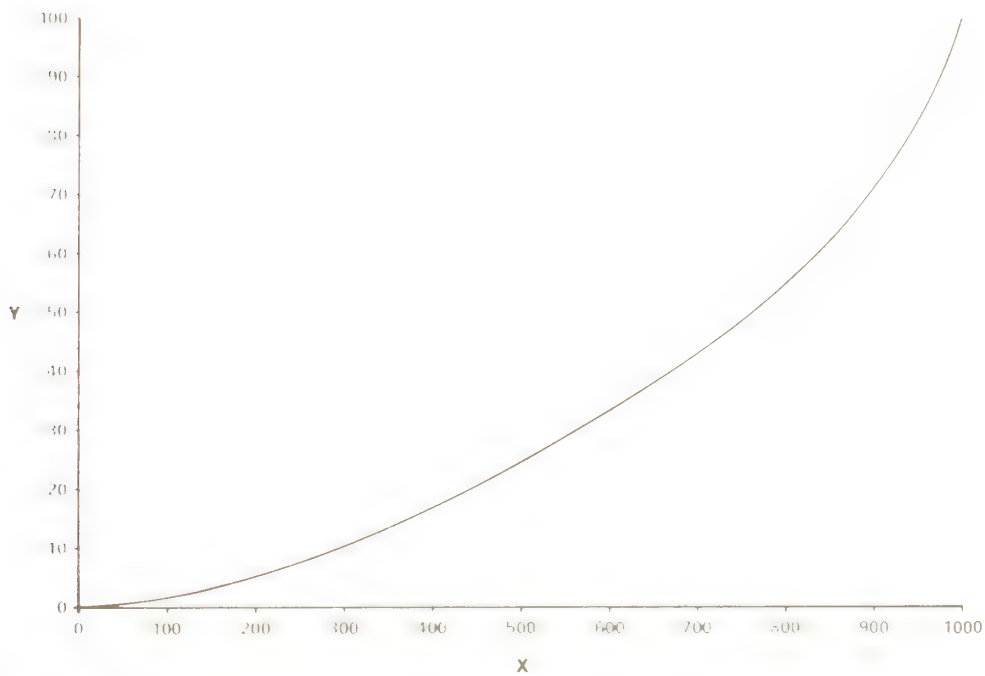


Figure 28.—A graphed hypothesis.

Assume this is the curve to be described. The discerning analyst will immediately reject it as a single-component X^n form because of the second pronounced bend in the range $700 \leq X \leq 1000$. But, let us run it through the X^n-single component procedures to provide a contrast for the two-component form to be developed subsequently.

Control points for the curve are normalized in table 10 and are replotted as a 5- by 7.5-inch overlay curve the same size as the Standards (fig. 29).

Table 10.—Normalized control points for figure 28

Control points		X =	$(Y-a)$ =	Overlay control points	
X (1)	Y (2)	$X1$ (3)	$Y1$ (4)	$X1/XP1$ (5)	$Y1/YP1$ (6)
0	0	0	0.0	0.00	0.00
200	5.2	200	5.2	.20	.05
400	17.0	400	17.0	.40	.17
600	33.5	600	33.5	.60	.34
700	43.0	700	43.0	.70	.43
800	54.8	800	54.8	.80	.55
900	71.1	900	71.1	.90	.71
1000	100.0	1000	100.0	1.00	1.00

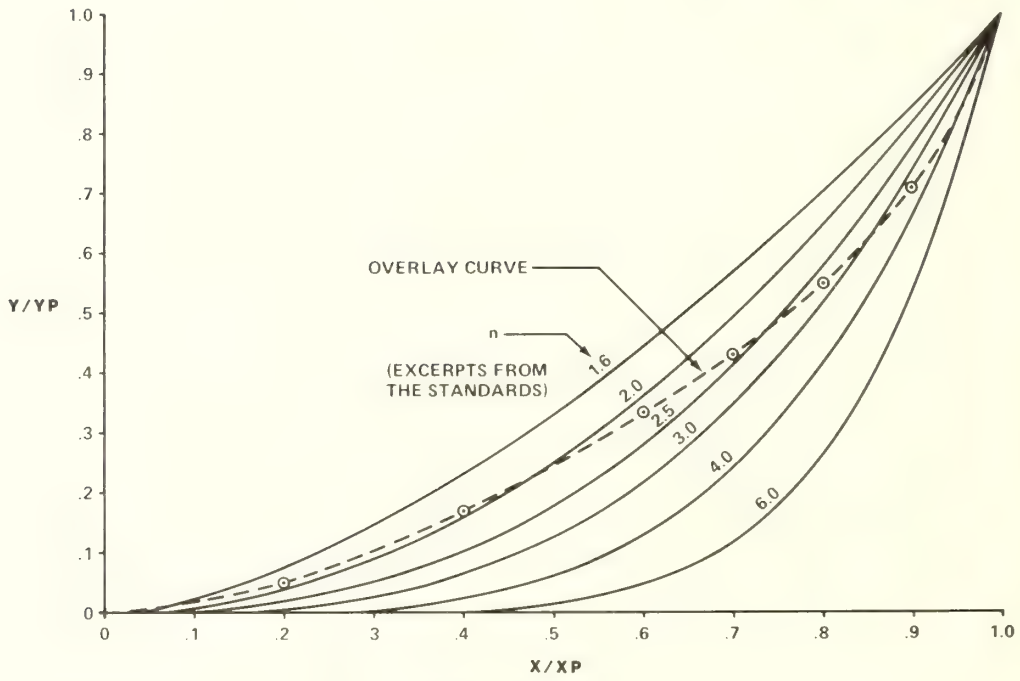


Figure 29.—Overlay curve for entire X-range compared to the X^n-Standards.

There is no suitable match for the overlay curve in the X^n-Standards; so we resort to description of the graphed curve with two components. The first component covers the range $0 \leq X \leq 700$ since that portion of the curve in figure 28 has only one point of bend and seems reasonably similar in conformation to the X^n-Standards. Next, X and Y are scaled to 1.0 at $X = 700$ (table 11, columns 1–4).

Table 11.—Mathematical hypothesis development

X	$(Y-a)$	Overlay control points 1st portion		† $bX^{1.65}$	Perform-ance of Y1	Overlay control points 2nd portion		†† $cX^{12.5}$	Perform-ance of Y2
X1 (1)	Y1 (2)	X1/700 (3)	Y1/43.0 (4)	Y1 (5)	(Y1 – Y1) (6)	X1/1000 (7)	Col.6 /22.5 (8)	Y2 (9)	(Y2 – Col.6) (10)
0	0.0	0.00	0.00	0.0	0.0			0.0	0.0
200	5.2	.29	.12	5.4	+ .2			0	– .2
400	17.0	57	40	17.1	+ .1			0	– .1
600	33.5	86	.78	33.3	– .2			0	+ .2
700	43.0	1.00	1.00	43.0	0			.3	+ .3
800	54.8			53.6	– 1.2	0.80	0.05	1.4	+ .2
900	71.1			65.1	– 6.0	.90	.27	6.0	.0
1000	100.0			77.5	– 22.5	1.00	1.00	22.5	0

†† $cYP1 \times XP_1^{12.5}$ = 22.5/(1000)$^{12.5}$

After plotting the first-portion overlay curve and comparing it to the X^n-Standards (fig. 30), we find that $X^{1.65}$ gives a good match for the curve in the $0 \leq X \leq 700$ range. Scaled to 43 at $X = 700$, $X^{1.65}$ gives a fairly close approximation of the $Y1$-values (table 11, column 6). As might be expected, this relatively flat curve is too flat when extended

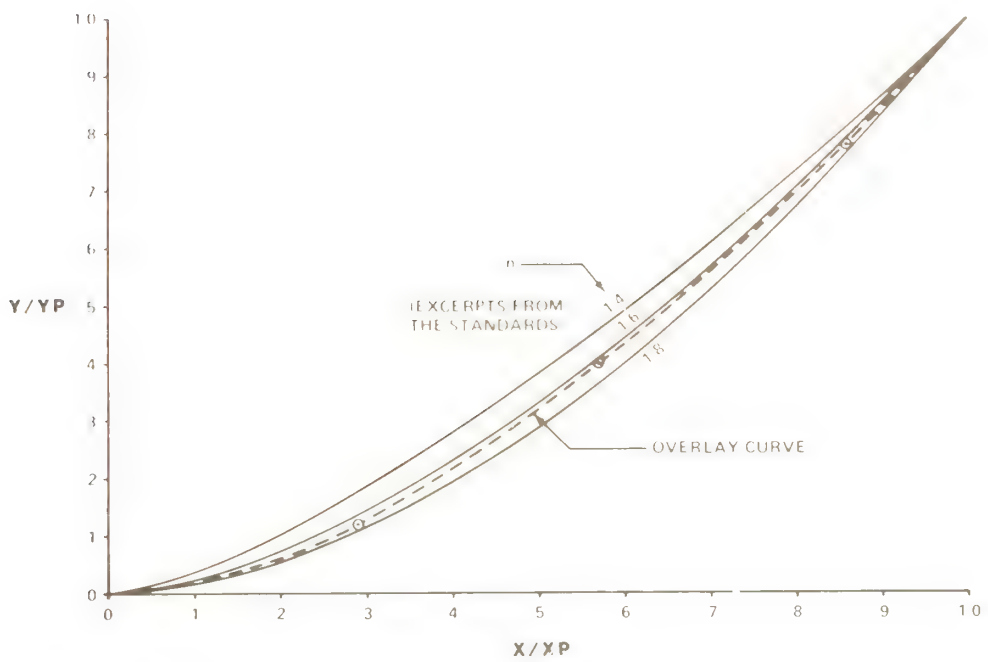


Figure 30.—First-portion overlay curve compared to the X^n-Standards.

to represent the desired curve in the $700 \leq X \leq 1000$ range (column 5). The differences, 1.2, 6.0, and 22.5, represent the curve of values that must still be added to match the right side of the desired curve. Needed in the descriptor is a second component that is essentially zero in the $0 \leq X \leq 700$ range and about equal to the curve of values still needed in the range $700 \leq X \leq 1000$.

Plotting the overlay curve for the second curve portion and comparing it to the X^n -Standards as in figure 31, we find that X^{13} might match the required curve fairly well

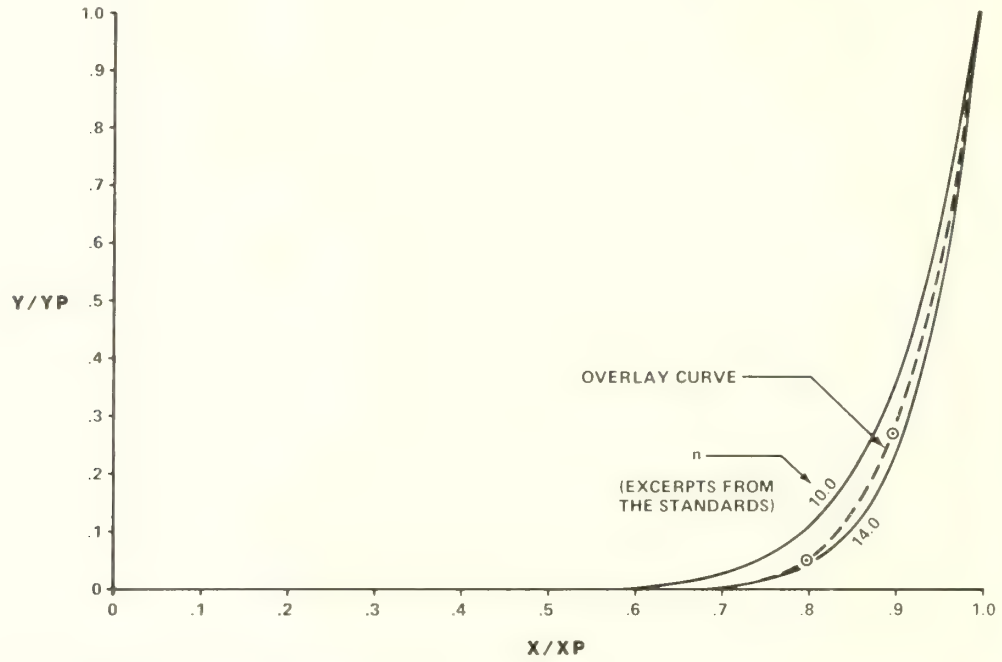


Figure 31.—Second-portion overlay curve compared to the X^n-Standards.

but, on trial, $X^{12.5}$ performs a little better. Scaling $X^{12.5}$ to 22.5 at $X = 1000$ gives values close to those desired in the $700 \leq X \leq 1000$ range (table 11, column 9). Then the complete descriptor is:

$$\hat{Y} = (8.691 \times 10^{-4}) X^{1.65} + (7.115 \times 10^{-37}) X^{12.5},$$

with final values listed in table 12. In this case, $\hat{Y}$ is regarded as being satisfactorily close to Y.

Table 12.—Model performance

X	Y	$\hat{Y}$
0	0.0	0.0
200	5.2	5.4
400	17.0	17.1
600	33.5	33.4
700	43.0	43.3
800	54.8	55.0
900	71.1	71.1
1000	100.0	100.0

The computational ideas just shown are applicable to other curve forms, but a larger array of ideas may be necessary to independent descriptor development efforts by the reader. The examples that follow are presented with decreasing explanatory detail as seems appropriate to the stage of discussion. We will start with an abbreviated version of descriptor procedures just presented in detail for the hypothesized curve in figure 28.

Two-Component X^n, No Inflection

• Read a set of representative XP points from the graphed hypothesis (fig. 32). Select one X-value in this set, point d, such that the curve over the range 0 to d appears to have about the same general conformation (one point of bend) as the X^n Standards.

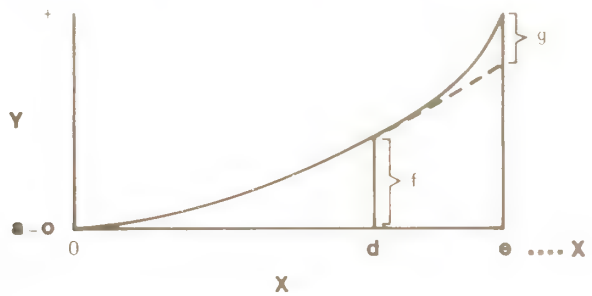


Figure 32.—The graphed hypothesis.

• Compare the corresponding overlay curve with the X^n-Standards and select an appropriate n in X^n.

• Scale X^n to f at d, $b = f/d^n$. Then, $Y1 = 2 + bX^n$. *Extend* $Y1$ over the range d to e (dashed line).

• Compare the overlay curve for the exponential curve of residuals over the range 0 to e with the X^n-Standards and select an appropriate m in X^m.

• Scale X^m to g at e, so that $c = g/e^m$. Then, $Y2 = cX^m$.

• Add components $Y1$ and $Y2$. Then, $Y = a + bX^n + cX^m$, and $a = 0$.

Alternative orientations of the above curve in space can be handled simply, as specified earlier in the section entitled "TWO DIMENSIONS".

Two-Component X^n, with Inflection

Figure 33 is a variant of the preceding sample. All steps of the descriptive process still apply, except that the second component is subtracted from the first. Then,

$$Y = a + bX^n - cX^m.$$

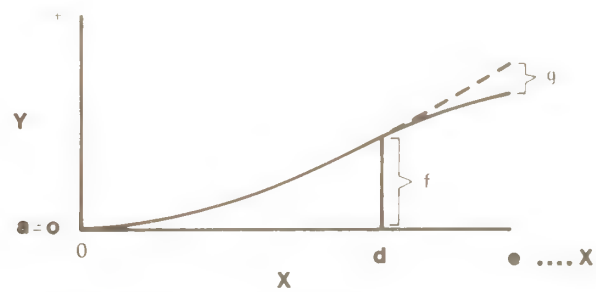


Figure 33.—The graphed hypothesis.

Again, alternative orientations of this curve in space can be handled as specified in the X^n-text, along with appropriate changes in sign for the last component.

Three-Component, X^n, with Flat Central Segment

The descriptor for a curve that has an extended flat midsection (fig. 34) can be treated as follows:

- Determine the intercept, a, by graphic extension of the flat segment. Calculate the slope of the line. Then,

$$\hat{Y}1 = a + bX.$$

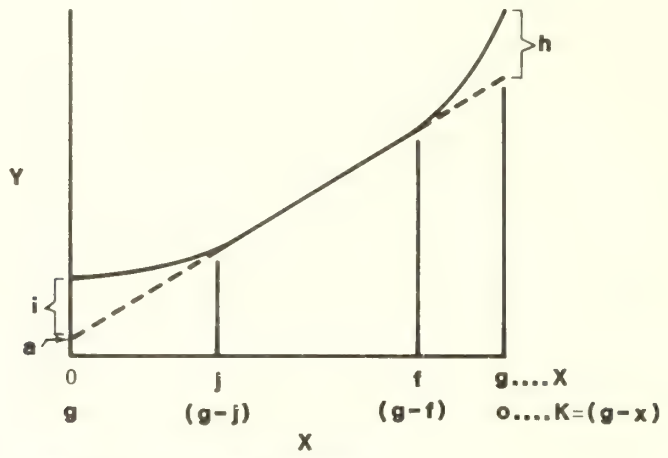


Figure 34.—The graphed hypothesis.

- Determine the residuals of the curve from the straight line for representative points over X. Include three or four such points at each end of X, where the curve bends away from the straight line.
- For the right-end departures, plot an overlay curve and compare to the X^n -Standards. Find a suitable n in X^n and scale X^n to h at g, wherein $c = h/g^n$. Then,

$$\hat{Y}2 = cX^n.$$

- For the left-end departures, plot an overlay curve and compare to the X^n -Standards. Reverse the X-axis by substituting $K = (f - X)$. Plot the left-end overlay curve and compare with the X^n-Standards. Find a suitable m in K^m and scale K^m to i at j; such that, $d = i/j^m$.
- Then, the left-end descriptor is:

$$\hat{Y}3 = dK^m.$$

Then the entire descriptor is:

$$\hat{Y} = a + bX + cX^n + dK^m, \; 0 \leq X \leq g.$$

Variants from this curve include negative departures from either or both ends of the straight line. In such cases, the signs of the corresponding components simply become negative.

Alternative orientations of this figure in space can be handled as specified earlier in "TWO DIMENSIONS".

Segmentation with X^n

Where X^n does not provide a suitably accurate descriptor for Y over the entire range of X, describing $Y = f(X)$ for each of several contiguous segments of the X-range, will often remedy the problem. In figure 35:

$Y = 1.0 + 6.456 \times 10^{-11} (X)^{5.9}$, $0 \leq X \leq 60$, results in departures from the objective curve of from $+0.03$ to -0.07.

$Y = 1.0$, $0 \leq X \leq 30$, and

$Y = 1.0 + 5.708 \times 10^{-4} (X - 30)^{2.4}$, $30 \leq X \leq 60$, results in departures of only ± 0.01.

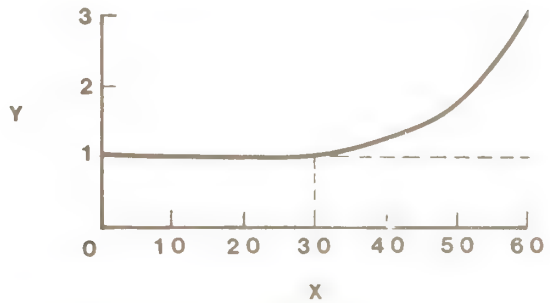


Figure 35.—The graphed hypothesis.

Straight-Line Slopes (X^n, $n = 1$) Plus or Minus Sigmoids

For any curve that has an inflection and a distinctive peak (positive or negative), $e^{\wedge}$-sigmoids may be appropriate. (Note that sigmoids may be created with two exponentials of opposite sign, as shown under multiple exponentials with inflection.) Sigmoids are shown here in combination with linear effects for added descriptive power.

In this case (fig. 36), we can use a straight line with slope $b = f/d$. The intercept plus the straight line is $Y1 = a + bX$. Then add to $Y1$ a sigmoid matching the curve differences, Yd, from the linear function, scaled to g at the point in X (e here) where Yd peaks. (Follow the methods in table 9.) The sigmoid component is $Y2 = ge^{\wedge}$.

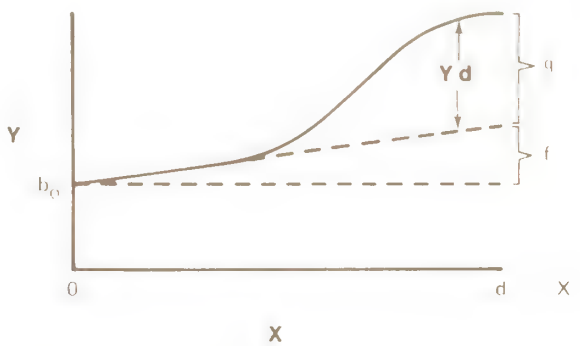


Figure 36.—The graphed hypothesis.

The final descriptor is then:

$$Y = a + bX + ge^{\wedge}$$

Alternative arrangements of the sigmoid about the straight line would require appropriate treatment (fig. 37a, b, and c).

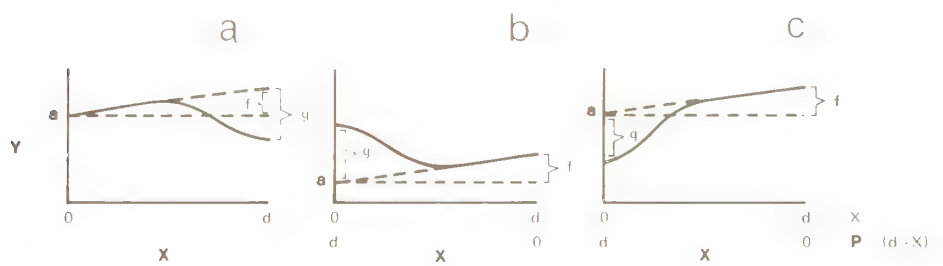


Figure 37.—The graphed hypotheses.

For figure 37a, $XP = d$ in the X-scale and the sign of the sigmoid component would become negative:

$$Y = a + bX - ge^{-K}.$$

For figure 37b, $P = (d - X)$ would be substituted for X in e^{-K}, $XP = d$ in the P-scale, and the sigmoids would be positive:

$$Y = a + bX + ge^{-K}, 0 \leq X \leq d.$$

For figure 37c, again, $P = (d - X)$ is substituted for X in e^{-K}, $XP = d$ in the P-scale, and the sigmoid is subtracted:

$$Y = a + bX - ge^{-K}, 0 \leq X \leq d.$$

The same sigmoid alternatives exist when the slope of the straight line is negative, the only change in the descriptors would be that the sign of the first component would be negative.

X^n, $n > 1$, Plus Sigmoids

Of course, exponentials and sigmoids can be used in combination (fig. 38). Where the left component is an X^n in P, subtracted from a, and the right component is a sigmoid in X added to a, then,

$$\hat{Y} = a - (f/d^n)P^n + ge^{-K}, 0 \leq X \leq d.$$

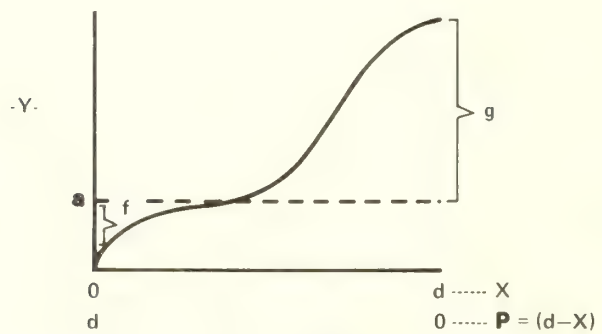


Figure 38.—The graphed hypothesis.

Multiple Sigmoids

Unsegmented

Sometimes the combination of several sigmoidal (upright or inverted) components can be used effectively to describe asymmetrical curves. Each sigmoid is matched and scaled independently and both are summed in the final descriptor.

For figure 39a, $P = (d - X)$ is substituted for X in e_L^{-K}, for the sigmoid to the left of c and e_R^{-K}, the sigmoid to the right of c, is described in the X-scale. $XP = d$ in X, for both X- and P-scales. Then,

$$\hat{Y} = a + fe_L{}^K + ge_R{}^K, 0 \leq X \leq d.$$

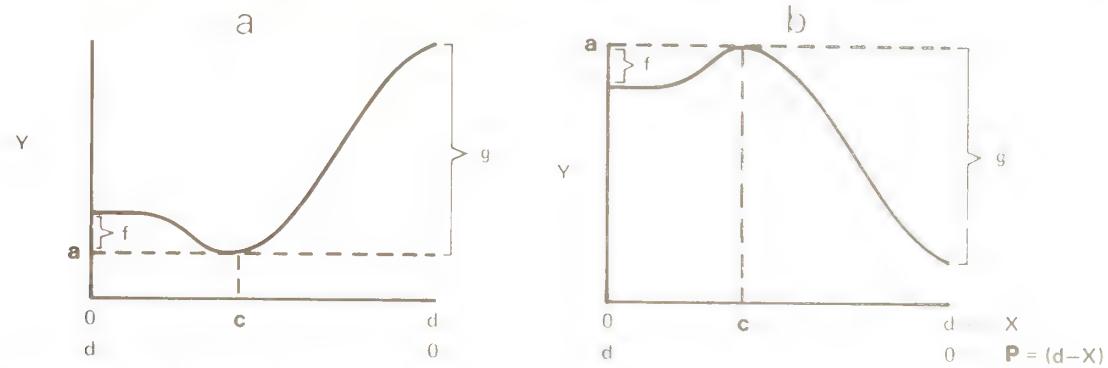


Figure 39.—The graphed hypothesis.

For figure 39b, the descriptor is much the same as for figure 39a, but the a-value is higher and signs of the sigmoidal effects are reversed. Then,

$$Y = a - fe_{\lambda} - ge_{\lambda}, \quad 0 \le X \le d.$$

Segmented

A simple way of handling asymmetry is to break the X range into two parts, $0 \le X \le XP$, and $XP \le X \le L$ (fig. 40). Identify a suitable sigmoid for each part of the skewed, bell-shaped curve and scale to YP using the X-scale for the left sigmoid and the $(L - X)$ scale for the one on the right. The result is a two-component descriptor

$$Y = YPe_{\lambda}, \quad 0 \le X \le XP$$

and

$$Y = YPe_{\lambda}, \quad XP \le X \le L.$$

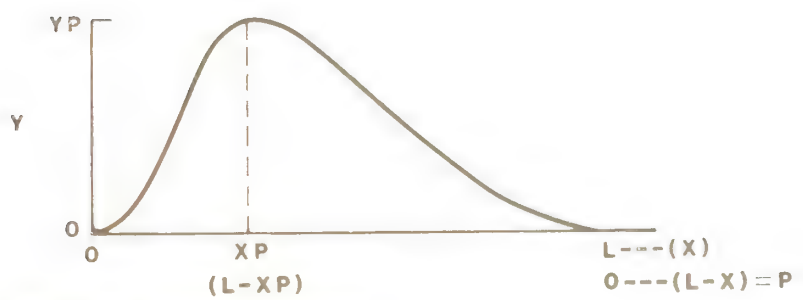


Figure 40.—The graphed hypothesis.

Contiguous Bell-Shaped Curves

Bell-shaped curves, in whole or in part, can be summed in a descriptor. And, for this particular example (fig. 41), the peaks of the two leftmost bell-shaped curves occur at points other than the upper or lower extreme of the X-range, which is not true in previous examples involving sigmoids. A peculiarity of $e^{-\lambda}$ is that its controlled use is within $XP + XP$, where XP is the point in the X-range at which the Y-peak (either positive or negative) occurs, and $XP \pm XP$ are the points at which the tails of the bell-shaped curve drop to zero. Beyond these points, the sigmoid values become negative. Then, where an XP is located in such a way that $XP \pm XP$ does not cover the pertinent range of X, it becomes necessary to alter the X-scale so that it does. The discussion below for the foregoing graph (fig. 41) should clarify both the problem and its solution.

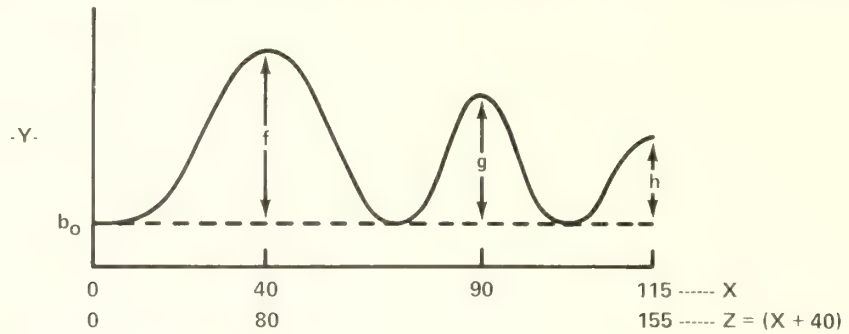


Figure 41.—The graphed hypothesis.

A symmetrical, bell-shaped curve with values ranging from 1.0 at XP to zero at $XP \pm XP$ is specified by e^{-K}. With $XP = 40$ for the first bell-shaped curve, the range of application for e^{-K} is 40 ± 40, or from zero to 80. Beyond $X = 80$, e^{-K} would actually dip below zero by some unspecified amount. The problem is simply remedied by adding a large enough constant to X such that $XP + XP$ in the new scale would cover the original maximum of 115. $P = (X + 40)$ accomplishes this nicely; so the descriptor would be:

For the first curve, $\hat{Y}1 = fe_1^{-K}$, where P replaces X in e^{-K} and $XP = 80$ in P;
For the second curve, $\hat{Y}2^5 = ge_2^{-K}$, where X is used without transformation in e^{-K}, since $XP = 90$ gives an applicable range for X of zero to 180, covering the X-extreme of 115 as required;
For the third curve, $\hat{Y}3 = he_3^{-K}$, where X is also used without transformation in e^{-K} since $XP \pm XP$ (115 ± 115) covers the pertinent range of X, $0 - 115$.
Then, the entire descriptor is:

$$\hat{Y} = a + fe_1^{-K} + ge_2^{-K} + he_3^{-K},\ 0 \leq X \leq 115$$

where: e_1^{-K} involves P
e_2^{-K} involves X
e_3^{-K} involves X.

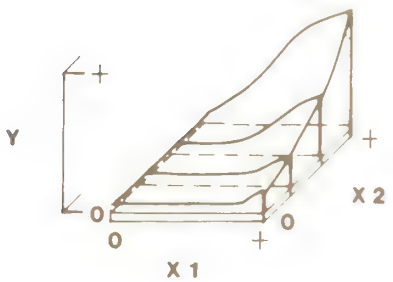
MATHEMATICAL DESCRIPTION OF GRAPHED HYPOTHESES - THREE DIMENSIONS

To reiterate what has been said prevously, the analyst's capability for developing sensitive multidimensional hypothesis models depends large on his or her 2-D talents. The examples shown here should provide enough procedural background to permit intuitive extension of the system to include more flexible curve-form alternatives. The **live** data examples included, serve to reinforce these ideas through application under real data circumstances.

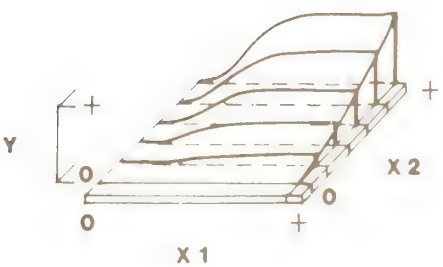
Outline for "THREE DIMENSIONS"

PAGE

Sigmoidal *X*1-Effect, with Constant Point of Peaking in *X*2 and Interacting with a Concave-Upward *X*2-Effect

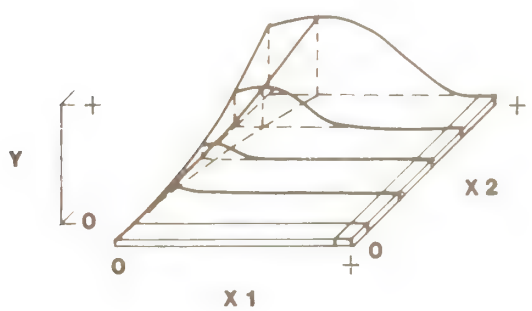


Contrived example 41



Live data example 43

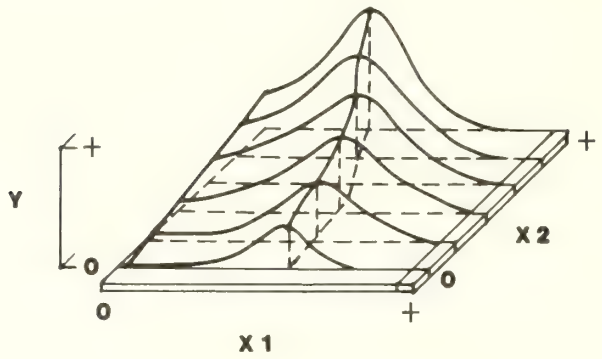
Symmetrical Bell-Shaped Ridge Over *X*1, with Moving Peak in *X*2 and Interacting with a Concave-Upward *X*2-Effect.



Live data example 47

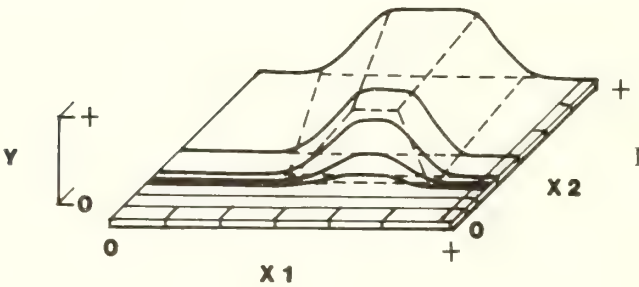
PAGE

Asymmetrical Bell-Shaped Ridge Over $X1$, with Moving Peak in $X2$. This is Described in Two Segments and Interacts with a Sigmoidal $X2$-Effect.



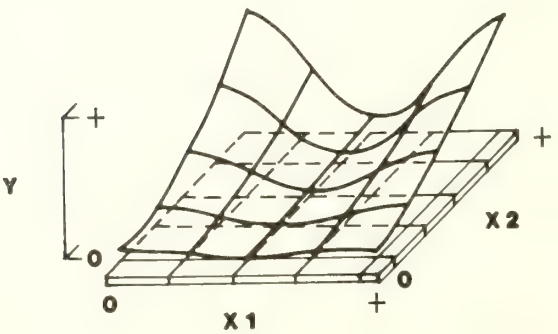
Live data example 63

Asymmetrical Bell-Shaped Ridge Over $X1$, with Moving Peak in $X2$. This is Described in Three Segments and Interacts with a Sigmoidal $X2$-Effect.



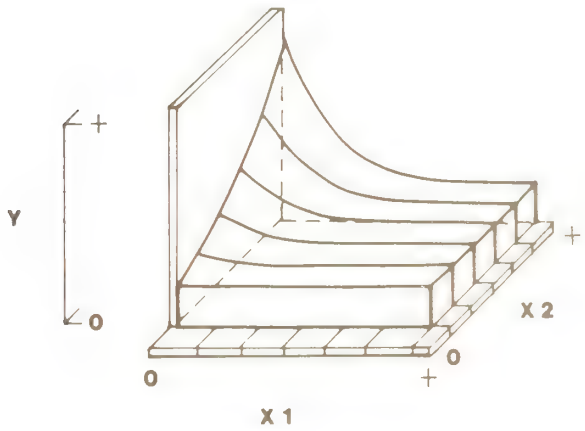
Live data example 69

Symmetrical, Inverse Bell-Shaped Ridge Over $X1$, with Constant Point of Minimum in $X1$ and Interacting with a Concave-Upward $X2$-Effect.



Live data example 73

Concave-Upward Relation in Two Dimensions, with Constant Point of Peaking in $X1$ Over $X2$.



Live data example 74

Sigmoidal $X1$-Effect, with Constant Point of Peaking in $X2$ and Interacting with a Concave-Upward $X2$-Effect

Contrived Example

Given graphed 2-D hypotheses over $X1$ for representative levels of $X2$ (fig. 42), and given the basic 2-D descriptor for the $X1$-effect (Y = intercept + scalar($X1$ sigmoid)) for each curve of the set, the analyst is in a position to formulate a descriptor for the implied surface. He simply expresses the changing intercepts, scalars, and parameter(s) of the $X1$-sigmoid in terms of $X2$ and then substitutes appropriately in the basic 2-D descriptor. Pertinent information for the four sigmoid curves above has been assembled in table 13, columns 1–6, by using information read directly from the graphs along with the X^n- and e^{λ}-Standards:

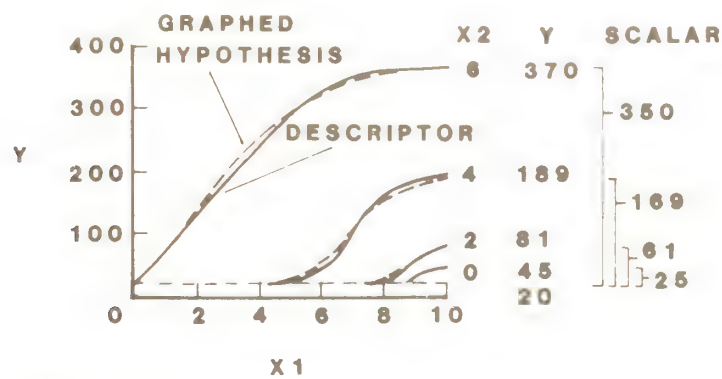


Figure 42.—The graphed hypothesis and descriptor performance.

Table 13.—Mathematical hypothesis development

	Sigmoid parameters						
$X2$ (1)	intercept (2)	XP (3)	n (4)	I (5)	scalar (6)	$\hat{I}$ (7)	scalar (8)
0	20	10	3.0	0.90	25	0.900	25.0
2	20	10	3.0	.87	61	.870	61.1
4	20	10	3.0	.66	169	.663	169.4
6	20	10	3.0	.10	350	.100	350.0

Here, the intercept and sigmoid parameters, XP and n, are constant over $X2$, but the scalar increases and I decreases exponentially with increasing $X2$-values. Using the X^n-Standards, $\hat{I} = 0.9 - 0.003704(X2)^3$ and $\hat{\text{scalar}} = 25 + 9.028(X2)^2$. These estimators perform rather well as may be seen in columns 7 and 8. Then substituting in the basic equation for $\hat{Y}$,

$$\hat{Y} = \text{intercept} + \text{scalar}(X1 \text{ sigmoid}),$$
$$\hat{Y} = 20 + (25 + 9.028(X2)^2)(X1 \text{ sigmoid})$$

where:

$$\text{The } X1 \text{ sigmoid} = \left\{ \frac{e^{-\left|\frac{(X1/10)-1}{1-I}\right|^3} - e^{-\left\{\frac{1}{1-I}\right\}^3}}{1 - e^{-\left\{\frac{1}{1-I}\right\}^3}} \right\}$$

and $\hat{I}$, as specified previously, $= 0.9 - 0.003704(X2)^3$.
Application limits for this hypothesis are $0 \le X1 \le 10$, and $0 \le X2 \le 6$.

By plotting computer solutions for $\hat{Y}$ at pertinent combinations of $X1$ and $X2$, we can see that the descriptor lies quite close to the graphed curves (fig. 42). And, the entire predicted surface appears as follows (fig. 43):

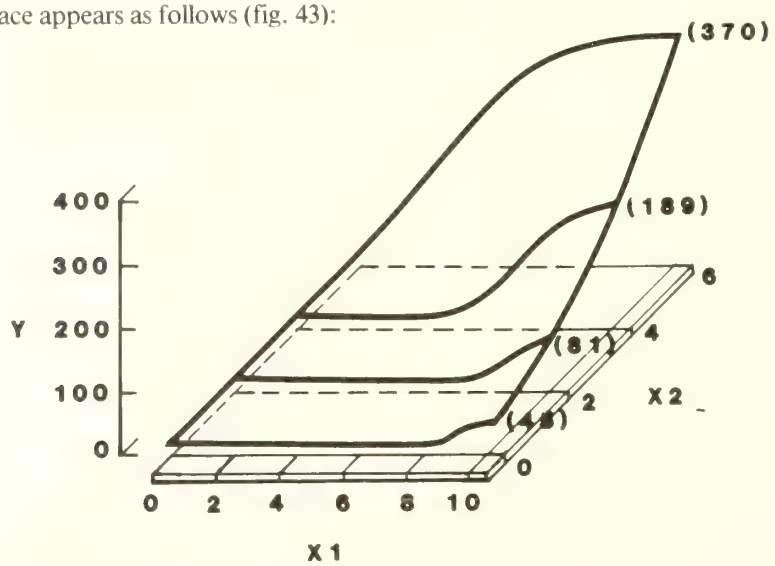


Figure 43.—The mathematical hypothesis.

Note that the original curves may be given over $X2$ instead of $X1$, in which case, the roles of $X1$ and $X2$ in descriptor development would be interchanged. Also, where multiple-component 2-D descriptors are involved, they are simply incorporated, like the single ones here, in the final descriptor.

This descriptor system is applicable to virtually any surface and is especially useful in emulating strong interactive relationships. An application to a live data set involving such interaction is documented in the next example as a means of demonstrating actual use of some of the 2-D alternatives available to the analyst.

Sigmoidal $X1$-Effect, with Constant Point of Peaking in $X2$ and Interacting with a Concave-Upward $X2$-Effect

Live Data Example

Wildlife managers have expressed interest in the thermal cover provided large game animals by the live crowns of lodgepole pine trees, as reported in Cole, D. M., and Jensen 1981. Related to such cover is the height to base of live crown (*HBC*) in lodgepole shown in figure 44 where *HBC* is expressed as a function of the average height of dominant trees (*H*) in the stand and stand density as reflected in Crown Competition Factor (*CCF*). This hypothesis reflects the expected effect for *CCF*, which is positive and sigmoidal, and that for *H* is positive with no strong expectation as to form.

These expected effects were found to exist in a data set dedicated to the formulation of a mathematical hypothesis for the relation. The 134 observations involved, were sorted into 10-foot height groups wherein *HBC* was plotted over *CCF* (fig. 45).

The expected sigmoidal *CCF*-effect was clearly visible in the data and appeared to break downward from the asymptotes at about the same point in *CCF* (180–200) for all height groups. The strongest expression of the sigmoidal form appeared to exist in the

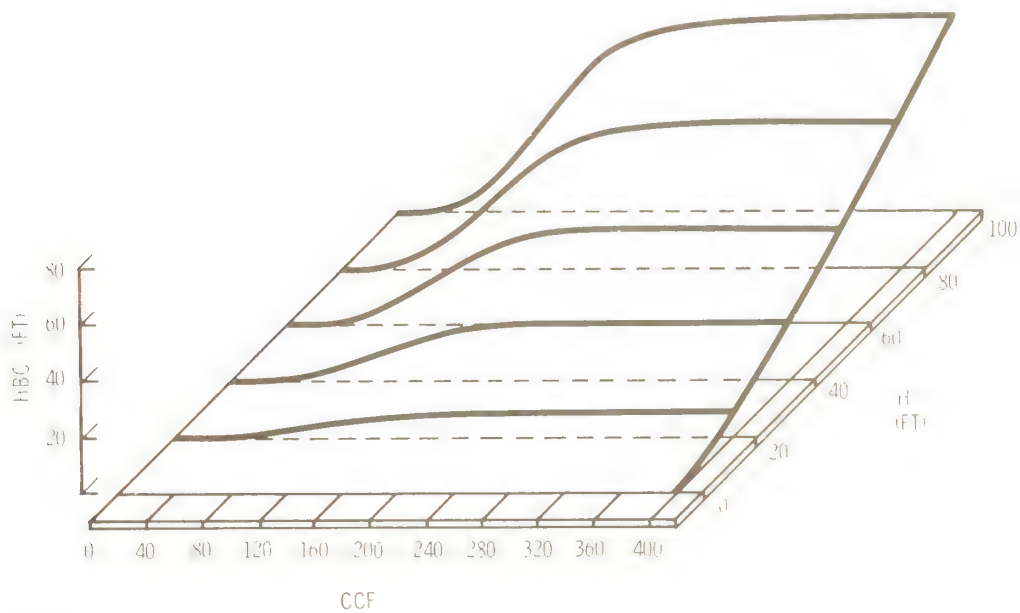


Figure 44.—The mathematical hypothesis.

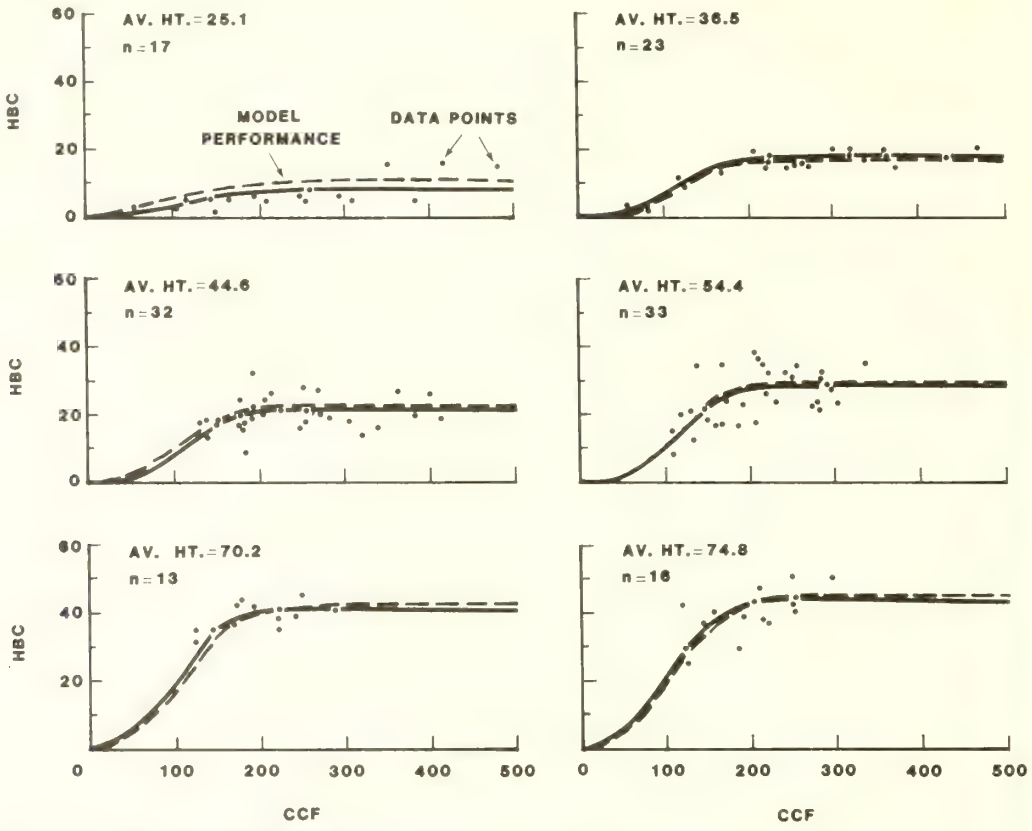


Figure 45.—Graphed hypotheses and model performance for partitioned data.

30- and 50-foot H-groups. Following procedures specified in the TWO DIMENSIONS text, control points were read from the approximate least deviations-fit, smoothed curves, and a specific sigmoidal form for each curve was determined (table 14) using the e^{-K}-Standards.

A single, unchanging sigmoidal form was suitably accurate in describing CCF effects at all heights. While the sigmoid, described by $n = 10$, $I = 0.183$, etc., provided the best match for the curve at $H = 36.5$ and that sigmoid with $n = 10$, $I = 0.190$, etc., was best for the curve at $H = 54.4$. An acceptable compromise was the sigmoid with I held constant at 0.186 (see the last column in table 14). Then, on simplifying,

$$\hat{HBC} = YP^{*}e^{-\left|\frac{CCF}{500}-1\right|^{10}},$$

where YP is the scalar for the sigmoids over H. Plotting and smoothing the heights of the graphed sigmoids (YP_i) at $CCF = 500$, a slightly concave-upward curve appears to exist (fig. 46).

Reading control points from the smoothed curve, a matching X^n-function was determined (table 15) from the X^n-Standards.

where, $b = 48.8/(80.0)^{1.37}$, and $\hat{YP} = 0.12056(H)^{1.37}$.

Table 14.—Mathematical hypothesis development

H	control points		Overlay control points		$n = 10, I = 0.183$, $XP = 500$, $YP = 18.0$, $a = 0$, *HBC1* =	Performance of *HBC1*	$n = 10, I = 0.186$, $XP = 500$, $YP = 18.0$, $a = 0$, *HBC2* =	Performance of *HBC2*
	CCF	*HBC*	*CCF*/500	*HBC*/18	$a + YP * e^{K}$	(*HBC1* – *HBC*)	$a + YP * e^{K}$	(*HBC2* – *HBC*)
36.5	80	5.0	0.16	0.28	4.8	– 0.2	4.6	– 0.4
	120	10.1	.24	.56	11.1	+ 1.0	10.9	+ 0.8
	160	16.1	.32	.89	15.3	– 0.8	15.3	– 0.8
	500	18.0	1.00	1.00	18.0	0.0	18.0	0.0

H	control points		Overlay control points		$n = 10, I = 0.190$, $XP = 500$, $YP = 29.5$, $a = 0$, *HBC* =	Performance of *HBC1*	$n + 10, I = 0.186$, $XP = 500$, $YP = 29.5$, $a = 0$, *HBC2* =	Performance of *HBC2*
	CCF	*HBC*	*CCF*/500	*HBC*/29.5	$a + YP * e^{K}$	(*HBC1* – *HBC*)	$a + YP * e^{K}$	(*HBC2* – *HBC*)
54.4	80	7.7	0.16	0.26	7.0	– 0.7	7.5	– 0.2
	120	16.3	.24	.55	17.4	+ 1.1	17.8	+ 1.5
	160	25.4	.32	.86	24.8	– 0.6	25.0	– 0.4
	500	29.5	1.00	1.00	29.5	0.0	29.5	0.0

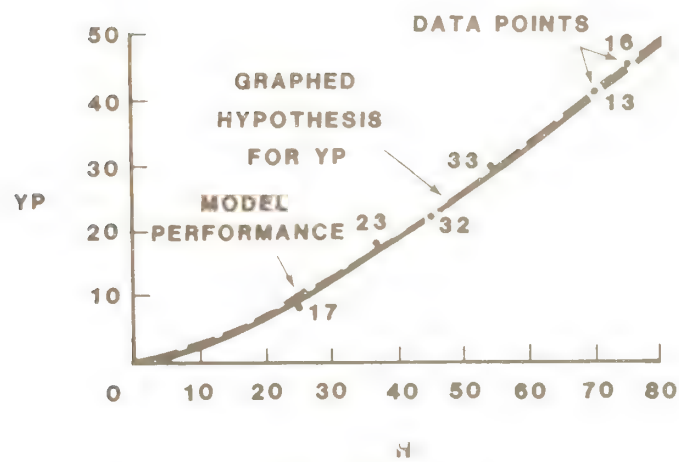


Figure 46.—Graphed hypothesis and model performance for *YP*.

Table 15.—Development of *YP*

Control points		Overlay control points		$b(H)^{1.37}$	Performance of *YP*
H	*YP*	*H*/80.0	*YP*/48.8	$\hat{YP}$	$(\hat{YP} - YP)$
25.1	9.3	0.31	0.19	10.0	+0.7
36.5	16.4	.46	.34	16.7	+ .3
44.6	21.0	.56	.43	21.9	+ .9
54.4	29.4	.68	.60	28.8	− .6
70.2	41.5	.88	.85	40.8	− .7
74.8	44.5	.94	.91	44.5	.0
80.0	48.8	1.00	1.00	48.8	.0

The complete hypothesis is then:

$$\hat{HBC} = (0.12056(H)^{1.37})^{*} e^{-\left|\frac{\frac{CCF}{500} - 1}{0.814}\right|^{10}}$$

with limits: $0 \leq CCF \leq 500$; $0 \leq H \leq 100$.

The performance of this model on the data from which it was partially derived ($R^2 = 0.87$) is shown as a dashed line within each *H*-group in figure 45. The final hypothesis presented in figure 44 is produced from model values in table 16.

Table 16.—$\hat{HBC}$ values from the model

AVH	*CCF*											
	40	60	80	100	120	140	160	180	200	300	500	
10	—	—	1	1	2	2	3	3	3	3	3	
20	—	1	2	3	5	6	6	7	7	8	8	← †
30	—	2	3	6	8	10	11	12	13	13	13	
40	1	2	5	9	12	15	17	18	19	20	20	← †
50	1	3	7	12	16	20	23	25	26	27	27	
60	1	4	9	15	21	26	29	32	33	35	35	
70	1	5	11	18	26	32	36	39	41	43	43	
80	2	6	13	22	31	38	43	47	49	51	51	
90	2	7	15	26	36	45	51	55	57	60	60	
100	2	8	18	30	42	52	59	64	66	69	70	

† Limits within which data were included.

The mathematical hypothesis, then, can be adjusted to data sets from different populations of trees through simple rescaling with $b = \Sigma XY/\Sigma X^2$, as is indicated in the TWO DIMENSIONS text.

Symmetrical Bell-Shaped Ridge Over *X*1 with Moving Peak in *X*2 and Interacting with a Concave-Upward *X*2-Effect

Live Data Example

George and Blakely (1973) reported on the calibration of fire-retardant dispersal from delivery aircraft. On each of 16 passes over a level target area, 600 gal of fire retardant were dropped from an aircraft. Square-foot coverage and volume of material reaching the ground per 100 ft^2 were measured for each aerial drop along with drop height, windspeed, wind direction, aircraft speed, temperature, and humidity. Interest finally centered on the change in coverage of ≥ 2 gal/100 ft^2 over a controlled range of drop heights within a partially controlled range of windspeeds. (The effects of all other variables were either negligible or unidentifiable in this data set).

If the plane were rolling along the ground (drop height = 3 ft) at normal flying speed and in the absence of wind, it would be expected that a 600-gal drop would be distributed over a relatively narrow strip of ground and that the area covered by ≥ 2 gal/100 ft^2 would be held to some nominal value. Increased aircraft (and drop) height should result in greater dispersal; maximum coverage should be reached at some optimal height. As drop height is increased beyond the optimum, dispersal of the retardant from air friction and evaporation should become more complete; coverage should finally reach zero at some relatively great drop height.

So expectation at zero wind is for a bell-shaped curve truncated to the left of the peak. With increasing wind, optimal drop height and peak coverage should diminish, since dispersal of the retardant would be accentuated by the horizontal shearing force of the wind. Thus, the expected surface would be as shown in figure 47.

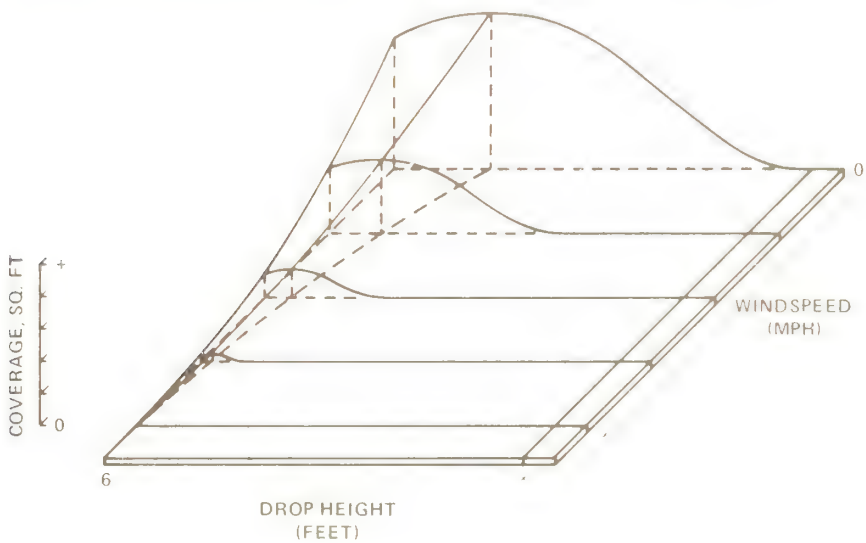


Figure 47.—The general expected relation.

Using these expectations as guides, coverage, C, was curved over height, H, fitting the curves to actual data points by approximate least deviations (Karst 1958) for each of three data groups in wind, W (fig. 48).

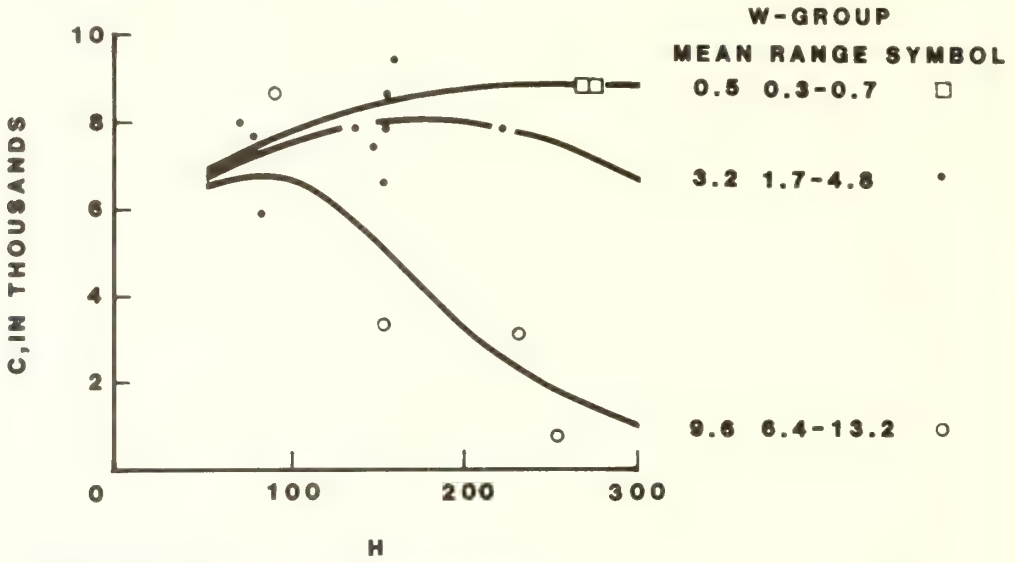


Figure 48.—Expected trends fitted through the data.

These curves, plotted at their respective W-means, were connected over W to form the implied surface, figure 49. And, it can be seen that major features of the expectation are reflected in the data—even within the limited range of H and W.

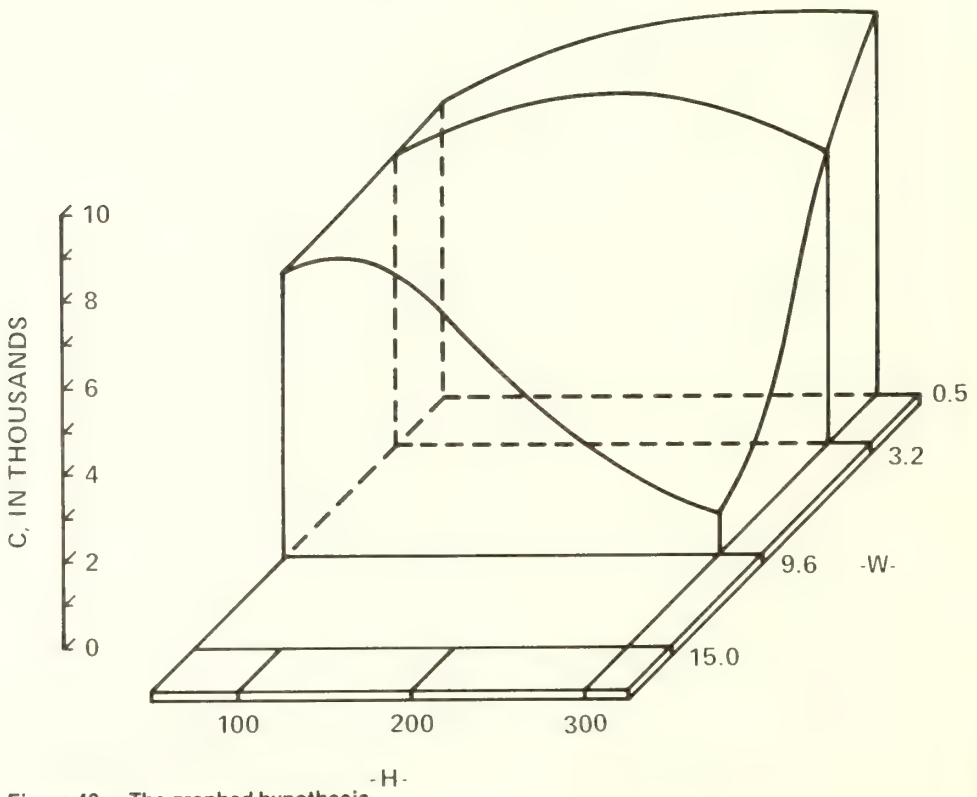


Figure 49.—The graphed hypothesis.

Figure 49, then, is the basic hypothesis for which a descriptor was developed. Assuming that the curves over H (fig. 48) could be suitably represented by segments of symmetrical bell-shaped forms, e^{-K} was deemed applicable and the identification of matching e-transforms was begun.

The e-transform is limited in that it will yield values of from zero to one in the full bell-shaped form only within the range $HP \pm HP$, where HP is the point in H at which the C-values peak. And, it was a unique feature of this example that the maximum H-values for all three curves of the set exceed $2HP$ (fig. 50).

Figure 50.—Graphed trends from figures 49 and 50, extended.

The broadest curve (for $W = 0.5$) was estimated to peak at $H = 273$. In this case, a matching e-transform would have dropped below zero where H exceeded $2HP$, or $2(273) = 546$, long before the approximate graphed limit of $H = 1150$ was reached. One solution here is to reverse the H-scale using as a base, the largest H-value of the broadest sigmoid likely to be encountered in the set of interest. Since an even broader sigmoid than $W = 0.5$ is expected to exist at $W = 0$, the largest H-value is estimated at $1150 + 100 = 1250$. The H-axis is then reversed using $X1 = (1250 - H)$ where, as may be seen in figure 50, $XP1 = 977$, 1072, and 1170 for $W = 0.5$, $W = 3.2$, and $W = 9.6$, respectively. Now, as required for each sigmoid, $XP1 \pm XP1$ includes both the largest and smallest value of $X1$ that will be encountered, and $X1 = (1250 - X)$ is used as the basis for the bell-shaped H-effect descriptor (e^{-K}). The coverage estimator is then specified as,

$$\hat{C} = CP1 \left\{ \frac{e^{-\left| \frac{(X1/XP1) - 1}{1 - I} \right|^{n}} - e^{-(1/(1-I))^{n}}}{1 - e^{-(1/(1-I))^{n}}} \right\}$$

where,

$C =$ coverage in square feet (≥ 2 gal/100 ft)
$X1 =$ (1250-H)
$XP1 =$ the point in $X1$ at which C peaks
$CP1 =$ coverage peak at $XP1$, scalar for the sigmoid
$I =$ the proportional point in $X1$ at which the inflection point of the bell-shaped curve occurs (a) in the range $X1 = 0$ to $XP1$ for the left half of the curve or (b) in the range $XP1$ to $2XP1$ for the right half (fig. 50).
$n =$ the power of the transform that dictates the degree of curvature above and below any inflection point.

Since the $XP1$- and $CP1$-values read from the three curves in figure 50 varied with wind in accord with expectation, they were each expressed as a suitable function of wind. Multiple-component X^n-descriptors were utilized.

$XP1$- and $CP1$- values from the foregoing equations along with representative paired $X1$- and C-values read from the left side of each bell-shaped curve were the basis for overlay curves. Standards for e^{-K} that were suitably similar to the overlay curves were identified, and the corresponding n (held constant) and I-values were recorded. Also, varying over wind in accord with expectation, I was described as a function of wind to complete the inputs to the coverage estimator. The details of these computations follow.

For $XP1 = f(W)$

Paired W- and $XP1$-values (0.5, 977; 3.2, 1072; and 9.6, 1170) were read from figure 50. These points were plotted and a smooth curve was drawn through them (fig. 51) that extended over the relevant range of W (0 – 15 mi/h).

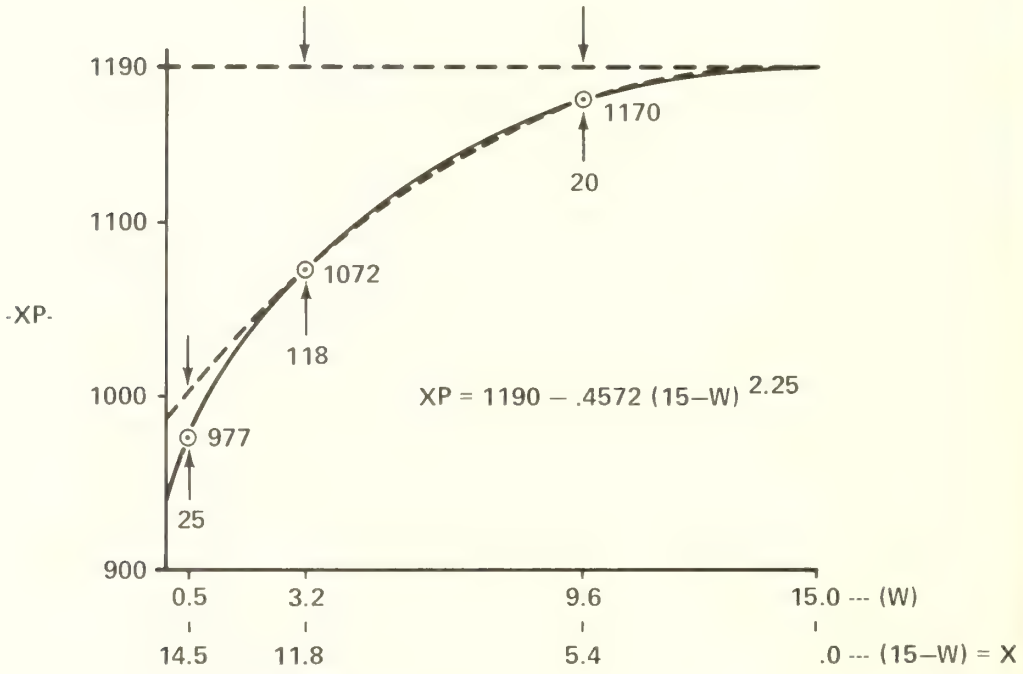


Figure 51.—Describing the *XP*-hypothesis.

The initial descriptor approach here was to subtract a single-component exponential curve on the reversed W-scale from the intercept, 1190 (table 17, columns 1–7). W was reversed in $X1 = (15 - W)$ to aline large values of the independent variable with those of $XP1$. Next, the three data point $X1$-values and associated coverage differences (absolute) from 1190 were scaled to 1.0 at $X1 = 14.5$. The overlay curve was not well matched by any curve in the X^n-Standards; so a two-component approach was adopted

Table 17.—Descriptor development for *XP*1

W =	*XP*1 =	(15 – *W*) =	(1190 – *XP*1) =	Overlay control points 1st segment		† $b(X1)^{2.25}$
X (1)	*Y* (2)	*X*1 (3)	*Y*1 (4)	*X*1/*XP*1 (5)	*Y*1/*YP*1 (6)	*Y*1 (7)
0.0	—	15.0	—	—	—	—
5	977	14.5	213	—	—	188
3.2	1072	11.8	118	1.00	1.00	118
9.6	1170	5.4	20	.46	.17	20
15.0	1190	0	0	.00	.00	0

	(15 – *W*) =	(*Y*1 – *Y*) =	Overlay control points 2nd segment		†† $c(X1)^{20}$ =	††† *XP*1 =
	*X*1 (8)	*X*2 (9)	*X*1/*XP*2 (10)	*Y*2/*YP*2 (11)	*Y*2 (12)	(13)
	15.0	—	—	—	—	936
	14.5	25	1.00	1.00	25	977
	11.8	0	.81	.00	0	1072
	5.4	0	.37	.00	0	1170
	0	0	.00	.00	0	1190

† $b = 1190 \div 11.8^{2.25}$ = 4.2[illegible]

†† $c = 25 \div 14.5^{20}$ = 1.4811 × 10[illegible]

††† $XP1 = 1190 - bX1^{2.25} - cX1^{20}$—which gives a perfect match for the original *XP*1-values at control points 0–14.5 in [illegible]

(table 17, columns 8–13). This time, the differences were fitted at $X1 = 0$, 5.4, and 11.8 to start with (see the dotted line below the intercept, 1190, in figure 51). Then, the difference (213 – 188 = 25) between the first-component curve and the desired curve was added in a second component. Computations are summarized in table 17, columns 8–13, and overlay curves are shown in figure 52.

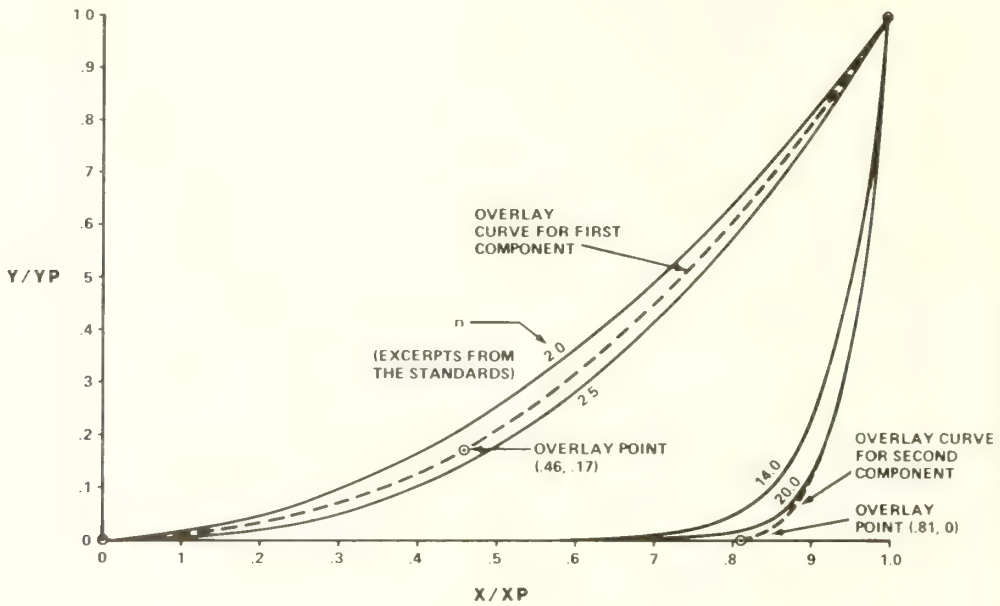


Figure 52.—First- and second-component overlay curves compared to the X^n-Standards.

The completed function was then

$$\hat{X}P1 = 1190 - 0.4572(15 - W)^{2.25} - 1.4811 \times 10^{-22}(15 - W)^{20},\ 0 \leq W \leq 15.$$

For $CP1 = f(W)$

Paired W- and $CP1$-values (0.5, 8900; 3.2, 8100; and 9.6, 6970) were read from figure 50. These points were plotted and a smooth curve was drawn through them (fig. 53) that extended over the relevant range of wind, 0–15 mi/h.

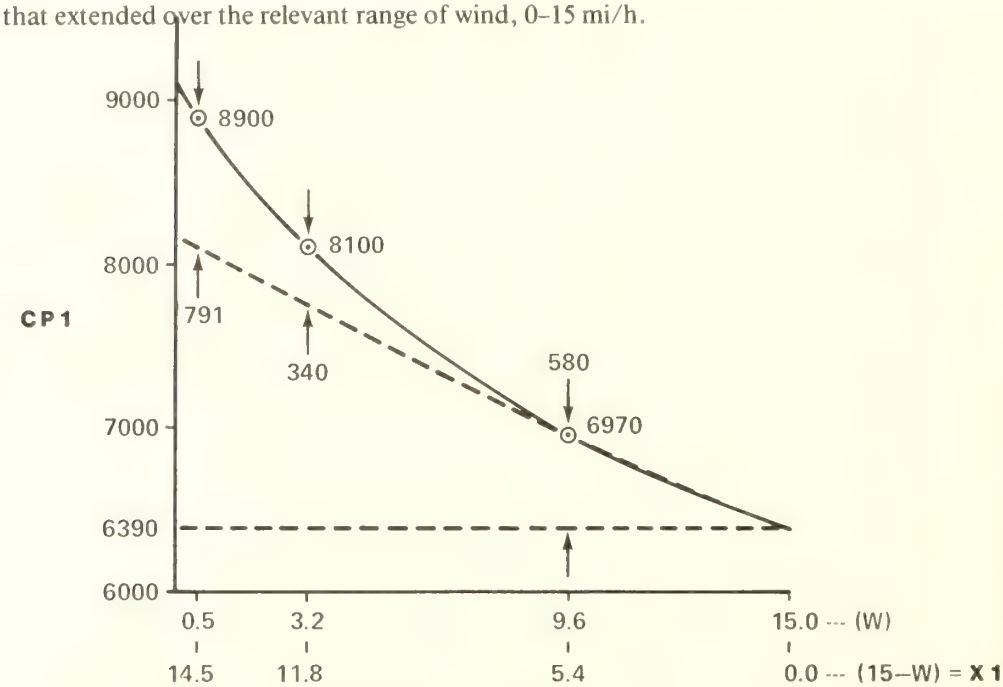


Figure 53.—A flat curve, $X^{1.1}$, matches the lower end ($9.6 \leq W \leq 15.0$) of the graphed hypothesis.

Again, a single-component exponential was first tried for the descriptor here (table 18, columns 1–7). Reversing the W-axis to $X1 = (15 - W)$ to aline large values of the independent variable with those of $CP1$, the $X1$- and $CP1$-values were scaled to 1.0 at $X1 = 14.5$. An overlay curve was constructed and compared to the X^n-Standards. But, none of the Standards were acceptably close to the overlay, so a two-component model was tried next (table 18).

To start with, the lower end of the curve ($0.0 \leq X1 \leq 15.4$) was fitted with an intuitively selected flat form ($X1^{1.1}$); it was obvious without scaling and overlays that the curve was extremely flat in that range of $X1$ (fig. 53). The component $X1^{1.1}$ was then scaled to the difference (580) between the intercept (6390) and the desired curve height (6970) at $X1 = 5.4$. So this first component (table 18, column 7), along with the intercept, 6390, constitutes the partial descriptor:

$$\hat{CP1} = 6390 + b(X1)^{1.1}.$$

Table 18.—Descriptor development for CP1

		(15 – W)	(CP1 – 6390)	Overlay control points 1st segment		† $bX^{1.1}$
W	CP1	X1	Y1	X1/5.4	Y1/580	Y1
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0.0	—	—	—	—	—	—
[illegible]	[illegible]	14.5	2510	—	—	1719
3.2	8100	11.8	1710	—	—	1370
[illegible]	[illegible]	[illegible]	580	1.00	1.00	580
15.0	6390	.0	0	.00	.00	0

		(15 – W)	(Y – Y1)	Overlay control points 2nd segment		†† cX^4	††† CP1
		X1	Y1	X1/14.5	Y2/791	Y2	
		(8)	(9)	(10)	(11)	(12)	(13)
		15.0	—	—	—	—	9080
		14.5	791	1.00	1.00	791	8900
		11.8	340	81	.43	347	8107
		5.4	0	37	00	15	6985
		0	0	00	00	0	6390

† $b = 580/(5.4)^{1.1} = 90.739$

†† $c = 791/(14.5)^4 = .001894$

††† $CP2 = 6390 + bX1^{1.1} + cX1^4$

This is the dashed line above the intercept (6390) in figure 53. The remaining differences, 340 and 791, and the associated $X1$-values were listed and scaled to 1.0 at $X1 = 14.5$ (table 18, columns 8–11). The overlay curve was then plotted and compared to the X^n-Standards (fig. 54).

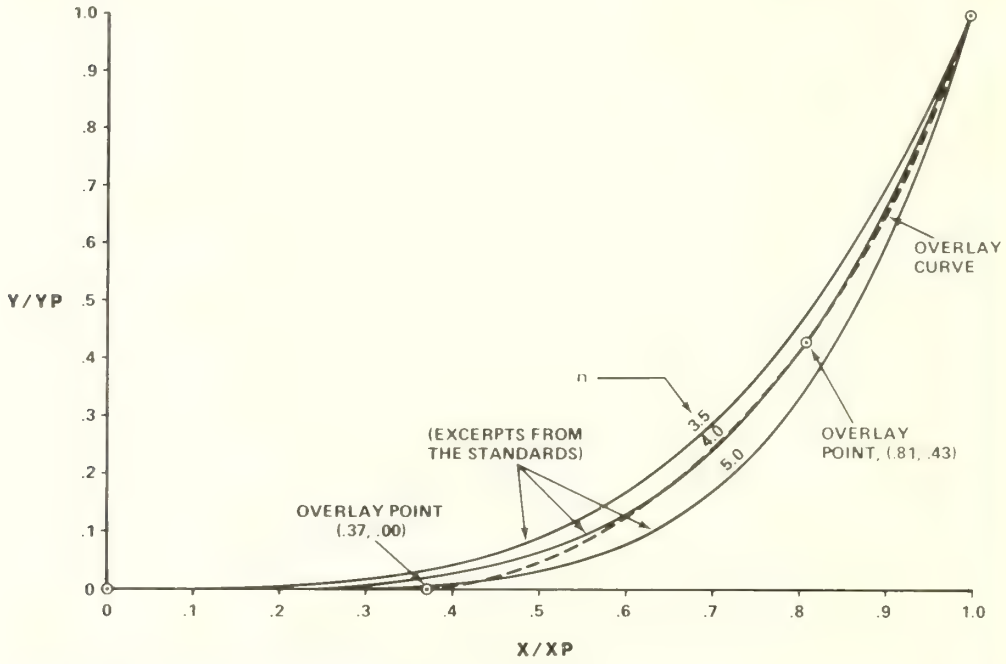


Figure 54.—Second component overlay curve compared to the X^n-Standards.

The curve $n = 4.0$ matched the overlay fairly well. So $(X1)^4$ was scaled to the difference, 791, at $X1 = 14.5$ (table 18, column 12). This was added to the intercept and the first component to arrive at the two-component descriptor, $\hat{C}P1 = 6390 + 90.739(15 - W)^{1.1} + 0.017894(15 - W)^4, \leq W \leq 15$. Note that the related estimates in table 18, column 13 were regarded as being satisfactorily close to the original objective values in column 2.

Matching the Bell-Shaped Curves

Tables 19 through 21 list $XP1$- and $CP1$-values from the equations developed in the foregoing sections along with some representative H- and C-values from the data-based portions of the bell-shaped curves in figure 50. Also listed are C-value estimates obtained by using matching e^{-K}-Standards (see the overlay curves in figure 55).

As may be seen in tables 19–21, the coverage values of the curve for each wind group were scaled to 1.0 by using the corresponding $\hat{C}P1$ as the maximum. The values of $X1$ or of $(2XP1 - X1)$ for each wind group were similarly scaled by using the corresponding $\hat{X}P1$ as the maximum. After the paired proportions for H-levels within each wind group were plotted and smoothed, the resulting overlay curves were compared to the e^{-K} -Standards for $n = 2$ (fig. 55). Although better matches for some of these overlays can be found in Standards that have n other than 2.0, it was decided to hold n constant

Table 19.—Descriptor development for C, $W = 0.5$

			(1250 – H) (2XP1 – X1) †		(C – a) ††	Overlay control points		†††
W	H	C	X1	T	Y1	T/977	Y1/8900	Y1
0.5	50	6860	1200	754	6860	0.77	0.77	7137
	100	7800	1150	804	7800	.82	.88	7793
	150	8450	1100	854	8450	.87	.95	8322
	200	8770	1050	904	8770	.93	.99	8692
	273	8900	977	977	8900	1.00	1.00	8900

† Temporary transform for plotting the overlay curve only. The temporary X1-values (T) must be in ascending order toward $XP1 = 977$ to match the position of the e^{-K}-Standards in two-space

†† All sigmoids of the set are oriented at a = zero, so $(C - a) = C = Y1$

††† Estimated coverage using e^{-K} with $X1 = (1250 - H)$, $I = 0.51$, $n = 2.0$, $XP1 = 977$, $CP1 = 8900$, and a zero intercept.

†††† Smoothed values from $XP1$ and $CP1$, each a function of wind (shown earlier in the text)

Table 20.—Descriptor development for C, $W = 3.2$

			(1250 – H) (2XP1 – X1)		(C – a)	Overlay control points		†
W	H	C	X1	T	Y1	T/1072	Y1/8107	Y1
3.2	50	6730	1200	944	6730	0.88	0.83	6843
	100	7600	1150	944	7600	.93	.94	7612
	150	8040	1100	1044	8040	.97	.99	8042
	178	8107	1072	1072	8107	1.00	1.00	8107

† Estimated coverage using e^{-K} with $X1 = (1250 - H)$, $I = 0.71$, $n = 2.0$, $XP1 = 1072$, $CP1 = 8107$, and a zero intercept.

over wind. Then, the I-values corresponding to the best matching curve alternatives in this set, were estimated to be 0.51, 0.71, and 0.88 for $W = 0.5$, 3.2, and 9.6, respectively. On scaling and checking these and alternative curves (by means of a small computer) at the tabled H-values within W-group, some improvement was achieved with the final I-array, 0.51, 0.71, and 0.88. The last column in each of tables 19–21 shows the final scaled coverage estimates. There was close proximity of these values to actual coverage, C, so $I = f(W)$ was developed next.

Table 21.—Descriptor development for *C*, $W = 9.6$

			† $(1250 - H)$	$(C - a)$	Overlay control points		†† Y
W	*H*	*C*	*X*1	*Y*1	X1/1170	Y1/6985	
9.6	80	6985	1170	6985	1.00	1.00	6985
	100	6820	1150	6820	.98	.98	6845
	150	5300	1100	5300	.94	.76	5448
	200	3270	1050	3270	.90	.47	3364
	250	1830	1000	1830	.85	.26	1612
	300	997	950	997	.81	.14	600

† Since the right half of this curve (fig. 50) was read, *X*1-values are already ascending toward $XP1 = 1170$ and no temporary transform of *X*1 is necessary for plotting the overlay curve.
†† Estimated coverage using e^{-K} with $X1 = (1250 - H)$, $I = 0.88$, $n = 2.0$, $XP1 = 1170$, $CP1 = 6985$, and a zero intercept.

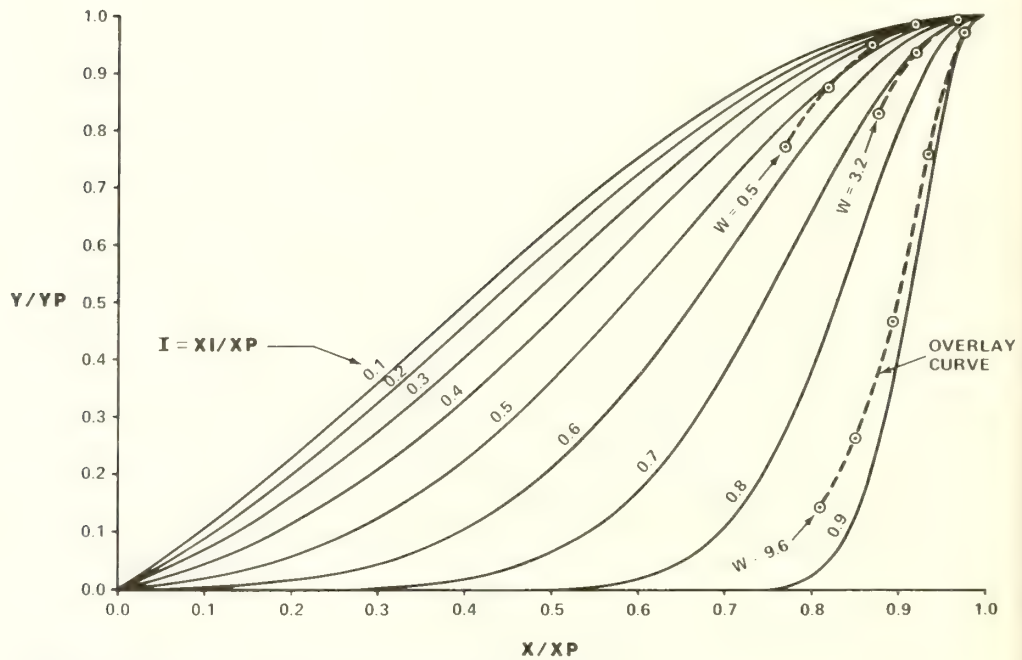


Figure 55.—Standards for $n = 2.0$ and proportional departure of inflection points in *X*, (*XI*), from *XP*, (*XI*/*XP*).

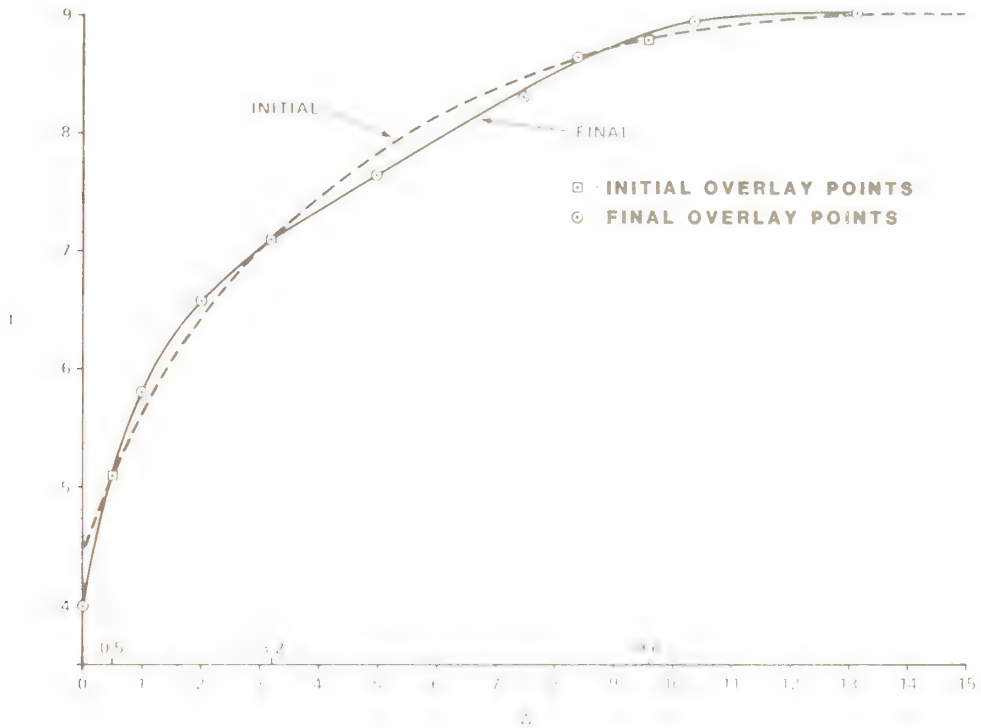


Figure 56.—Initial and final curves of *I* over *W*.

For $I = f(W)$

Using the paired wind and *I*-values just determined (0.5, 0.51; 3.2, 0.71; and 9.6, 0.88), *I* was plotted over *W* and a smooth *initial* curve drawn through the three data points (fig. 56).

On checking the performance of e^{K} over the range of *W*, with smoothed *CP*-, *XP*-, and initial *I*-values, it was found that the left edge of the surface undulated unacceptably (at $H = 50$, $0 \leq W \leq 5$). *I*-values were adjusted iteratively to minimize the problem and the new (final) set of points shown in figure 56 were established. The smooth (final) curve through these points became the objective curve for which a descriptor was developed.

This curve was judged to require a multicomponent model because neither the sigmoids nor the exponentials have the flattened central segment found there. The flat segment was represented by a straight line; the negative differences at the left end by an exponential; and those at the right by the lower portion of a sigmoid (fig. 57).

The Flat Segment.—A straight line was drawn along the final curve. The intercept, $a = 0.62$, and values necessary to the coefficient for *W*, $(1.054 - 0.620)/15 = 0.0289$, were read directly from the graph. Then *Y*1, the first descriptor component, $= 0.620 + 0.0289(W)$, (see table 22, column 3).

The Left End.—This residual portion of the curve ($Y2$) was satisfactorily matched by a single exponential of the reversed *W*-axis ($\hat{Y}2$), scaled at $X1 = 14.5$ (table 22, columns 4–8).

So the partial form at this point is:

$$\hat{Y}\,(\text{partial}) = 0.62 + 0.0289(W) - 4.3703 \times 10^{-21}(15 - W)^{16.75}.$$

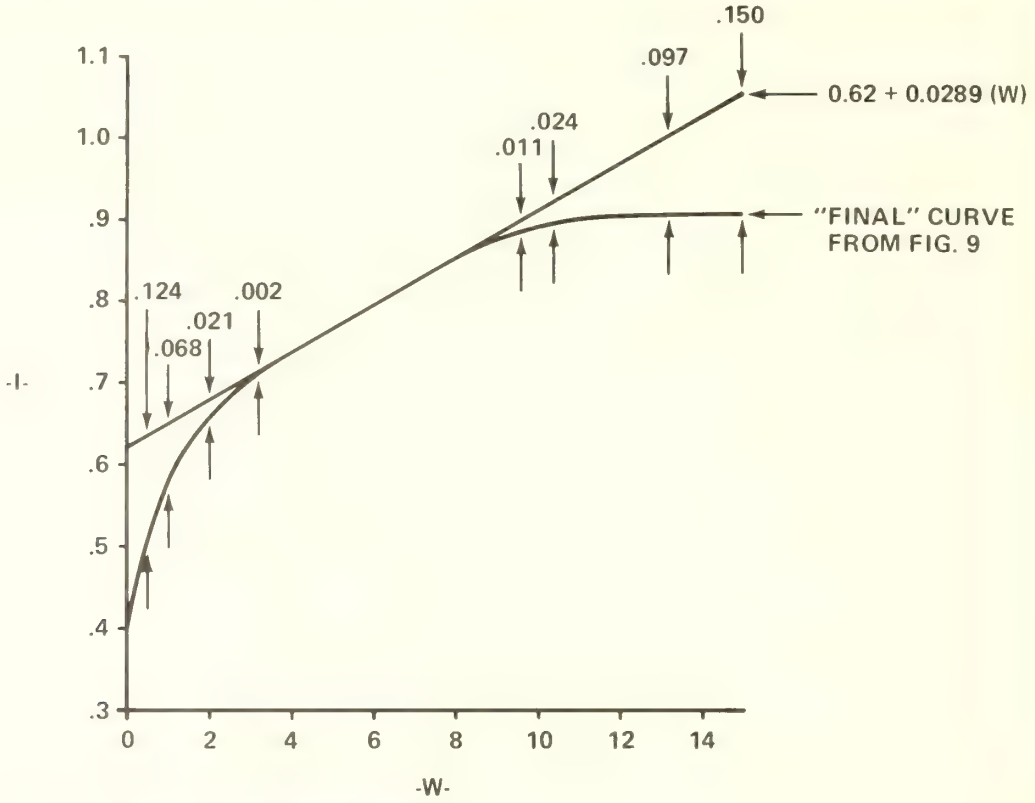


Figure 57.—Elements of $I = f(W)$, graphed.

Table 22.—Descriptor for $\dot{I}$, the *left end* and *central segment*

	I =	$a + b(W)$ =	$(15 - W)$ =	$(\dot{Y}1 - Y1)$ =	Overlay control points		† $cX^{16.75}$
W (1)	Y1 (2)	$\dot{Y}1$ (3)	X1 (4)	Y2 (5)	X1/14.5 (6)	Y2/0.124 (7)	$\dot{Y}2$ (8)
0.0	0.400	0.620	15.0	0.220	—	—	0.219
.5	.510	.634	14.5	.124	1.00	1.00	.124
1.0	.581	.649	14.0	.068	.97	.55	.069
2.0	.687	.678	13.0	.021	.90	.17	.020
3.2	.710	.712	11.8	.002	.81	.02	.004

† Although not shown in the text here, the curve implied by the overlay points matched $16 \leq n \leq 17$ in the X^n. Standards very well. Iterative checking showed $n = 16.75$ to perform best within that range. Then, $c = 0.124/(14.5)^{16.75} = 4.3703 \times 10^{-21}$

The Right End.—For this portion of the curve, the differences ($Y3$) from the straight line and associated scaling information are listed in table 23. It is apparent in figure 58 (right side) that the objective curve is not well matched by any simple power of W. The same held true for a multiple-component descriptor that was subsequently developed. By

Table 23.—Descriptor for *I*, the *right end*

		$a + b(W)$	$(Y1 - I)$	† Overlay control points	
W	*I*	Y1	Y3	*W*/15	Y3/0.150
(1)	(2)	(3)	(4)	(5)	(6)
8.4	0.863	0.863	0.000	0.56	0.00
9.6	.886	897	011	.64	.07
10.4	.897	921	.024	69	16
13.2	.904	1.001	.097	88	.65
15.0	904	1.054	.150	1.00	1.00

† The overlay curve is compared to the X^n-Standards at the right side of figure 58

reorienting the exponential curve in space, however, reversing W to $X1 = (15 - W)$ and inverting $Y3$ to $Y4 = (0.15 - Y3)$, the curve becomes convex-upward with increasing values of $X1$. Also, it is at least roughly matched by the sigmoid Standard, $n = 8$ and $I = 0.108$ (see table 24 and the left overlay curve in fig. 58). This sigmoid was the result of an interpolation between the two Standards $I = 0.1$ and 0.2 at $n = 8$.

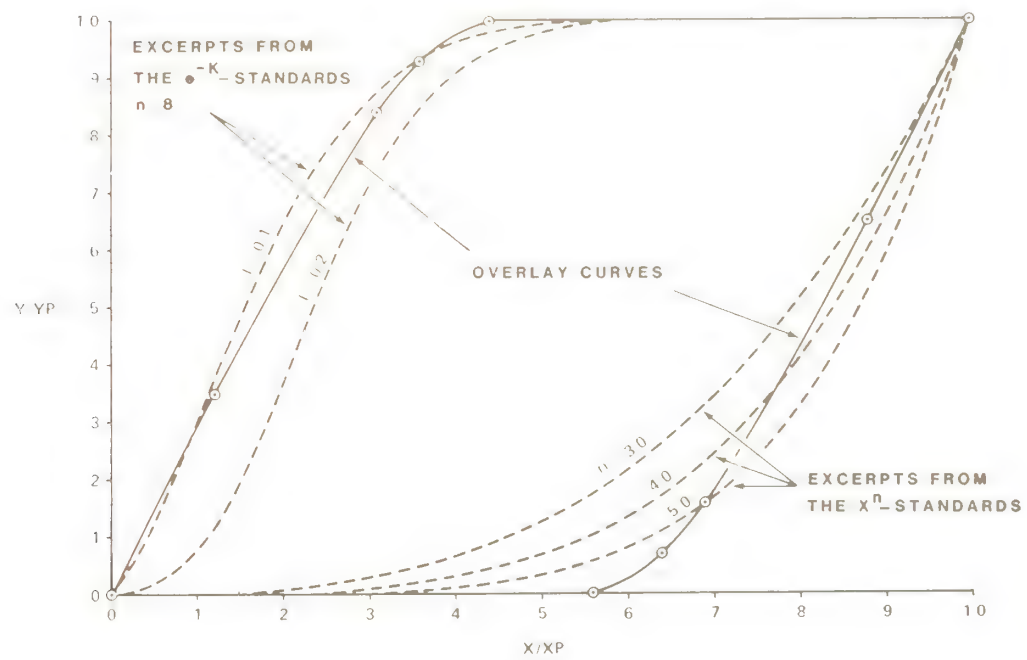


Figure 58.—Overlay curves compared to the Standards.

Table 24.—Descriptor (continued) for $\dot{I}$, the right end

	$(15 - W)$ =	† $(Y1 - I)$ =	$(0.150 - Y3)$ =	Overlay control points		†† de^{-K} =
W (1)	$X1$ (2)	$Y3$ (3)	$Y4$ (4)	$X1/15$ (5)	$Y4/0.150$ (6)	$\dot{Y}4$ (7)
0.0	15.0	—	0.150	1.00	1.00	0.150
8.4	6.6	0.000	.150	.44	1.00	.146
9.6	5.4	.011	.139	.36	.93	.139
10.4	4.6	.024	.126	.31	.84	.130
13.2	1.8	.097	.053	.12	.35	.053
15.0	.0	.150	.000	.00	.00	.000

† From table 23, column 4.
†† e^{-K} using $X1$, $n = 8$, $I = 0.108$, $XP1 = 15.0$, $YP = 0.150$, and the intercept, $a = 0$.

Then, the right end was specified as:

$$\hat{Y}4 = (0.15 - Y3) = 0.150(e^{-K})$$
$$\hat{Y}3 = 0.150 - 0.150(e^{-K})$$

$$\hat{Y}3 = 0.150 - 0.150\left\{\frac{e^{-\left|\frac{(15-W)}{15} - 1\right|^{8}_{1-0.108}} - e^{-\left\{\frac{1}{1-0.108}\right\}^{8}}}{1 - e^{-\left\{\frac{1}{1-0.108}\right\}^{8}}}\right\}$$

and simplified:

$$\hat{Y}3 = 0.16349e^{-\left|\frac{(15-W)}{15} - 1\right|^{8}_{0.892}}.$$

The three components were assembled for $\hat{I}$.—

$$\hat{I} = 0.62 + 0.0289(W) - 4.3703 \times 10^{-21}(15 - W)^{16.75} - 0.16349e^{-\left|\frac{(15-W)}{15} - 1\right|^{8}_{0.892}}.$$

The overall performance of this descriptor can be seen from the tabulation of the objective and estimated I in table 25, where I and $\hat{I}$ were suitably close over the range of W, as already verified by segment during development.

Table 25.—The performance of I

W	Objective I	$\hat{I}$
0.0	0.400	0.401
5	.510	.510
1.0	.531	.580
2.0	.657	.658
3.2	.710	.709
5.0	.766	.764
7.5	.838	.835
8.4	.863	.859
9.6	.886	.886
10.4	897	.900
13.2	.904	.905
15.0	.904	.904

Summary for C′

At this point, all necessary inputs have been derived and the complete hypothesis is:

$$C' = CP1 \left\{ \frac{e^{\frac{(X1/XP1)-1}{1-I}} - e^{-(1/(1-I))^2}}{1 - e^{-(1/(1-I))^2}} \right\}$$

where:

C' = coverage in square feet, estimated from the preleast squares fit motel
$CP1$ = coverage peak for any specified windspeed, W, and
$CP1 = 6390 + 90.739(15 - W)^{1.5} + 0.617894(15 - W)^4$, $0 \le W < 15$
$X1 = (1250 - H)$
H = drop height, $50 \le H \le 300$
$XP1$ = point in $X1$ at which $CP1$ occurs, or
$XP1 = 1190 - 0.4572(15 - W)^{2.25} - 1.4811 \times 10^{-22}(15 - W)^{20}$
I = inflection point in X expressed as a proportion of XP, ($X1/XP$ in Matchacurve-1, Jensen and Homeyer 1970),

$$\hat{I} = 0.62 + 0.0289(W) - 4.3703 \times 10^{-21}(15 - W)^{16.5} - 0.16349e^{-\left(\frac{(15-W)}{0.892}\right)^8}.$$

The hypothesis was then adjusted back to the data from which it was partially derived following the fitting procedures discussed under 2-D, X^n and e^{-K}, where $C' = X$ and the simple least squares adjustment coefficient for the entire hypothesis,

$$b = \Sigma XY / \Sigma X^2 = 1.000569 \text{ and } \hat{C} = bC'.$$

The coefficient, b, is very near 1.0000; so it is evident that even before least-squares adjustment, the original hypothesis was well alined with the data spatially. But, in checking the form of the hypothesis by comparing predicted ($\hat{C}$) and actual (C) coverages in figure 59, at least one anomaly appears. Actual coverage data points for the three high-wind points ($W = 8.4$, 10.4 and 13.2) probably lie too close to the surface since substantial variation occurs about the surface at lower wind levels; i.e., reasonable variance about the surface would be expected at high-wind levels also.

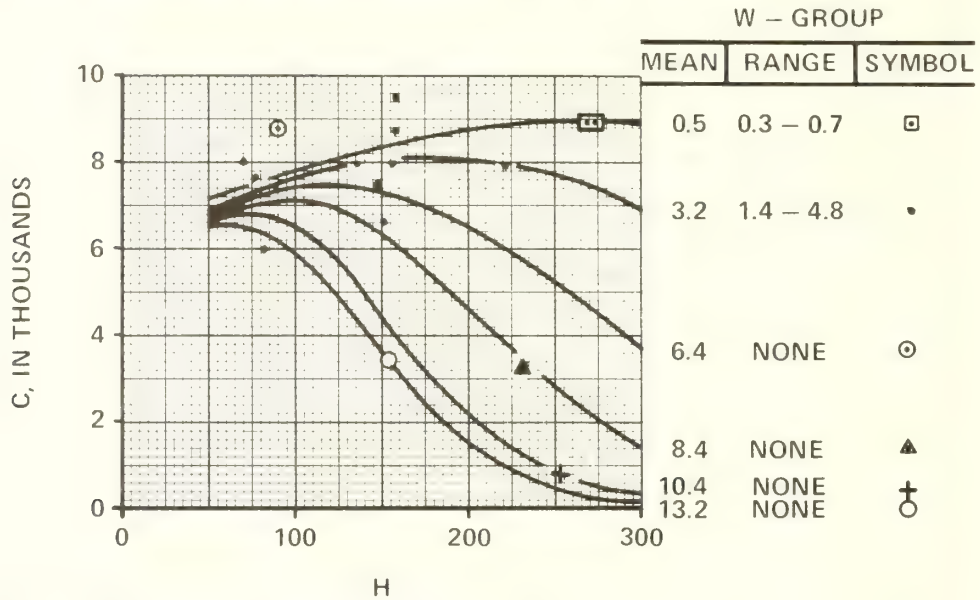


Figure 59.—Hypothesis performance by wind group.

Recall that through the use of controlled I-values (fig. 56) for curves passing close to the three high-wind points, low variation of these points from the surface was assured. Alternative I-values could be used that would allow for variation from the surface, in accord with some assumed variance criteria. This refinement was not attempted and the model was adopted as developed. Predicted values (table 26) and the associated surface (fig. 60) for the model are as shown below.

Table 26.—Model values

	Drop height					
Wind	**50**	**100**	**150**	**200**	**250**	**300**
mi/h	---------- *Feet* ----------					
0	7,198	7,804	8,316	8,710	8,969	9,081
5	6,830	7,525	7,707	7,337	6,491	5,338
10	6,617	6,707	4,925	2,619	1,009	282
15	6,345	5,663	3,460	1,447	414	81

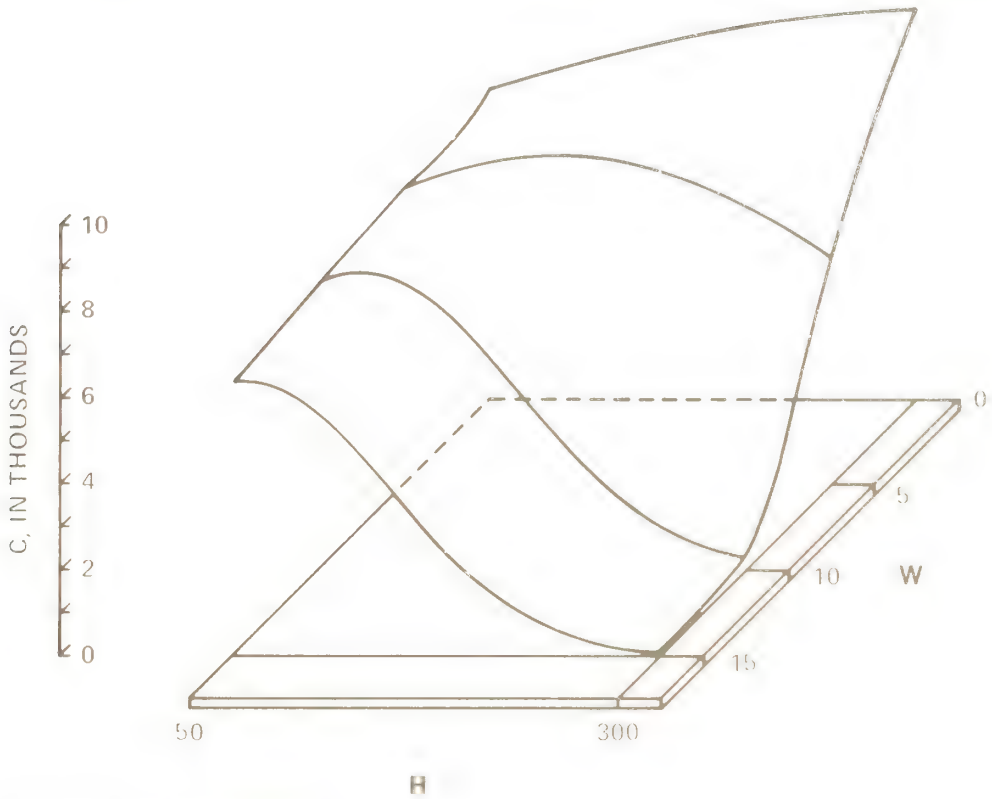


Figure 60.—The 3-D hypothesis.

It is appropriate to review the imposing list of constraints that can be met in models like this one. Controllable items include: the intercept for the whole surface; the elevation, breadth, and positioning of the peaks over the interacting independent variables; the trend in coverage at the truncated left edge of the surface; the magnitude of curvature above and below the inflection points in the bell-shaped curves; and the positioning of the inflection points themselves within the range of the independent variables.

Asymmetrical Bell-Shaped Ridge over $X1$, with Moving Peak in $X2$. This is Described in Two Segments and Interacts with a Sigmoidal $X2$-Effect

Live Data Example

In this hypothesis from Klein, Parker, and Jensen 1978, tree mortality percent in a western forest is characterized by tree diameter (d.b.h.) over the course of a beetle epidemic (fig. 61).

The graphed hypothesis is applicable only at discrete points in time and at the midpoints of 2-inch d.b.h. classes, but both variables are treated as continuous. As was evident in the original data, the more-or-less bell-shaped trends over time differ substantially on either side of the central ridge. For example, observe strong asymmetry at

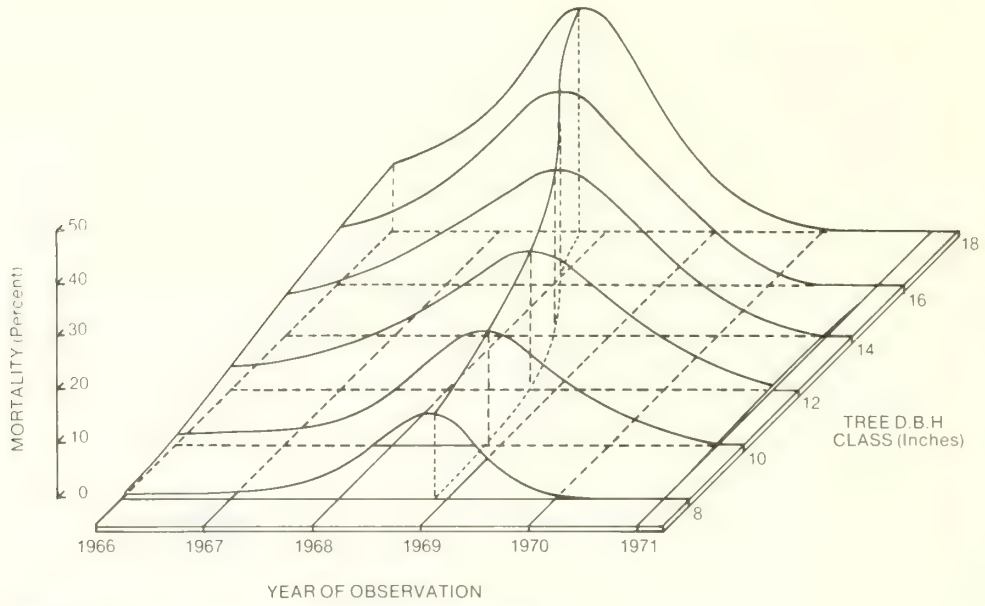


Figure 61.—Tree mortality over the course of a beetle epidemic.

d.b.h. = 12 to 18 inches, made most noticeable perhaps by elevational differences in the curves at their left and right extremes. See also the dwindling breadth of curve crowns above and below 15 inches d.b.h., an interactive change included in the descriptor along with asymmetry.

To assemble descriptor components, left and right sides of the ridge were described separately (fig. 62 and 63), using sigmoids from the e^{-K}-Standards that varied in shape and scale according to data trends over d.b.h. Because the lower portion of curves of the left half were asymptotic at values larger than zero, it was necessary to include the left-edge intercept, *Int*, or floor, upon which the left-side sigmoids rested conceptually. *Int* is a function of d.b.h., as is *XP*, the location of the ridge in time.

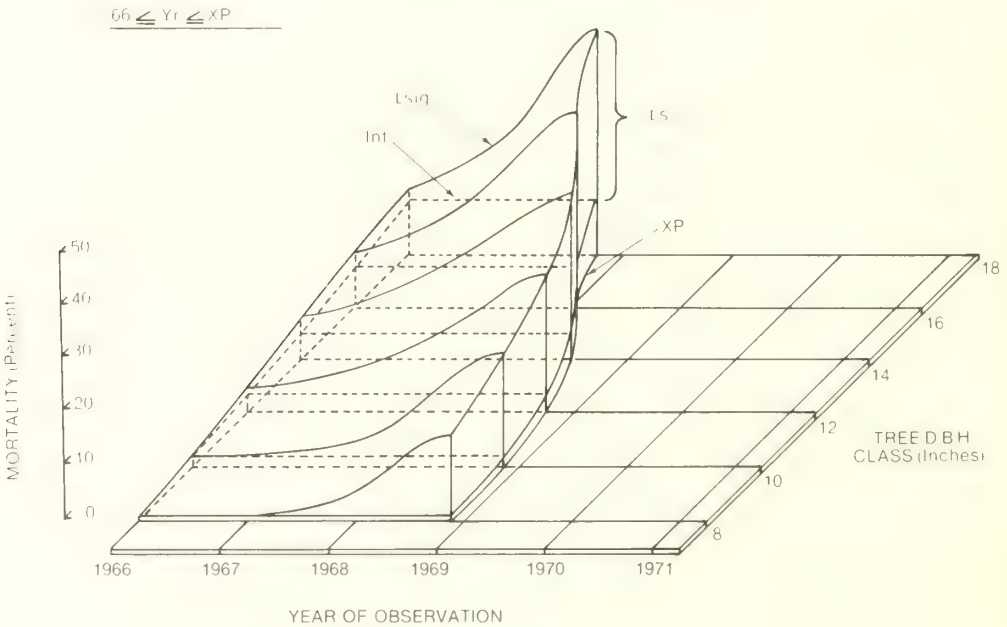


Figure 62.—Tree mortality over the course of a beetle epidemic, *left segment*.

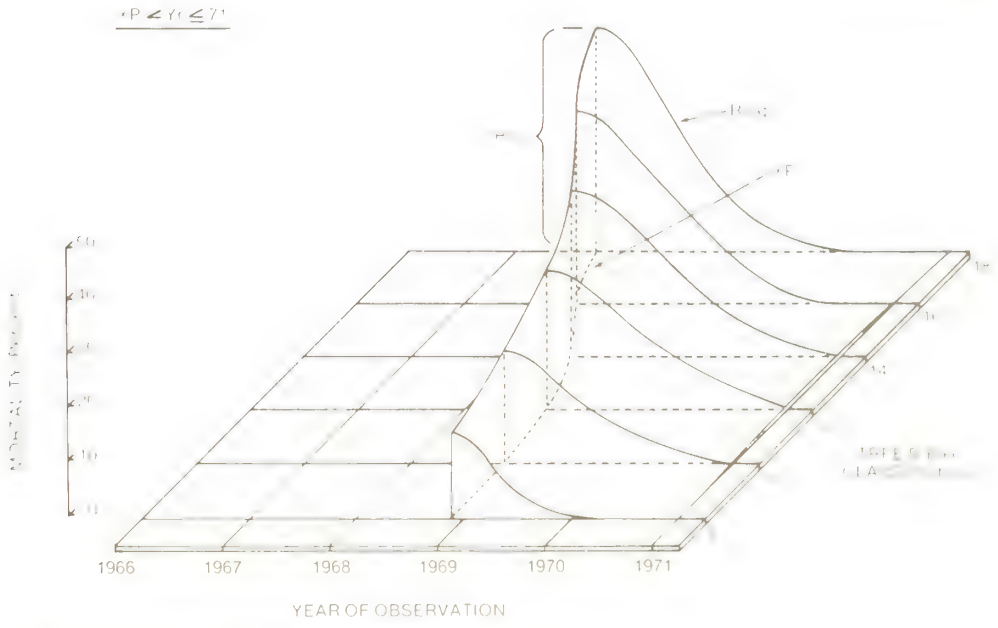


Figure 63.—Tree mortality over the course of a beetle epidemic, *right segment*.

Sigmoids are described within the range $XP \pm 5$ years (Yr), since all sigmoids are estimated to be fully expressed therein. Use of a constant maximum range, such as $XP \pm 5$ years, keeps descriptor components to a minimum for the sigmoidal time effects, yet permits satisfactory matching of the objective curves in this case. Restated in general terms, the whole descriptor is as follows:

Mortality percent = $Int + Lsc(Lsig) + Rsc(Rsig)$

where

$Lsig$ = left sigmoid = $f_l(Ln, LI, XP, Yr)$. See the basic sigmoid parameters defined in Jensen 1979.

$Ln = Lsig$ power = f_1(d.b.h.)

$LI = Lsig$ inflection point as a proportion of the range in years from $XP - 5$ to XP, = f_2(d.b.h.)

XP = point in time where surface peaks = f_3(d.b.h.)

$Rsig$ = right sigmoid = $f_R(Rn, RI, XP, Yr)$

$Rn = Rsig$ power = f_4(d.b.h.)

$RI = Rsig$ inflection point as a proportion of the range in years from $XP + 5$ to XP, = f_5(d.b.h.)

Int = intercept, left edge = f_6(d.b.h.)

$Rsc = Rsig$ scalar = ridgetop = f_7(d.b.h.)

$Lsc = Lsig$ scalar = (ridgetop) − (Int)

Segmental constraints:

Left side; $66 \leq Yr \leq XP$, discrete values only

Right side; $XP \leq Yr \leq 71$, discrete values only

Either side; $8 \leq$ d.b.h. ≤ 18, midpoints of 2-inch d.b.h. class only . . . 8, 10, 12, etc.

The model, refitted by least squares to smoothed mortality percent at 36 control points on the original data cross sections over time resulted in an R^2 of 0.96. Used as a

goodness-of-fit index, this high R^2-value attests to the fact that the descriptor duplicates the objective graph with reasonable accuracy.

The explicit hypothesis and moderate developmental detail follow:

Mortality percent $= K(Int + Lsc[Lsig] + Rsc[Rsig])$

where

K = least-squares coefficient = 0.9877

$Int = 1 + 0.2321(\text{d.b.h.} - 8)^{1.63}$

$Rsc = 2.6429(\text{d.b.h.}) - 5.157$

$Lsc = Rsc - Int$

$$Lsig = \left\{ \frac{e^{-\left|\frac{\frac{5-|Yr-XP|}{5}-1}{1-LI}\right|^{Ln}} - e^{-\left(\frac{1}{1-LI}\right)^{Ln}}}{1-e^{-\left(\frac{1}{1-LI}\right)^{Ln}}} \right\}$$

$$XP = 67.65 + 1.2257e^{-\left|\frac{\frac{20-\text{d.b.h.}}{12}-1}{0.65}\right|^{3.9}}$$

$$LI = 0.851 - 0.1531e^{-\left|\frac{\frac{7-|\text{d.b.h.}-13.5|}{7}-1}{0.45}\right|^{2}}$$

$Ln = 1.5$

$Rsig$ = as for $Lsig$, but using RI and Rn

$RI = 0.752 + 7.8173 \times 10^{-4}|\text{d.b.h.} - 14|^{2.8}$

$Rn = 2$

Limits

$66 \leq Yr \leq 71$, discrete units only

$66 \leq Yr \leq XP$, for Int, Lsc, $Lsig$

$XP < Yr \leq 71$, for Rsc, $Rsig$

$8 \leq \text{d.b.h.} \leq 18$.

Supplementary Explanatory Detail

Int was estimated from leftward extension (from the ridge) of the mortality trend indicated by data in each of six 2-inch d.b.h. groups. All six trends reached lower asymptotes by 1963 and, at that point, suggested a flat, concave-upward curve over d.b.h. (fig. 64). This was satisfactorily described by using the X^n-Standards.

Rsc is simply the height of the ridge above zero (no intercept) and serves as the scalar for the right-half sigmoids. ***Rsc*** is a linear function of d.b.h. adopted to represent the somewhat irregular pattern of ridge values for the six d.b.h. groups (fig. 65). Note that the ridge line in figure 62 only appears to be sigmoidal by reason of the sigmoidal change of point-of-peaking in time with a change in diameter.

Lsc = (*Rsc* − *Int*) and is the scalar for the left-half sigmoids.

XP, the point in time at which the bell-shaped curves peaked, was estimated from the *XP*'s for the six data-group cross sections (fig. 66). This curve was estimated to asymptote at 68.88 for lower diameters and 67.75 for higher diameters. A suitable match was

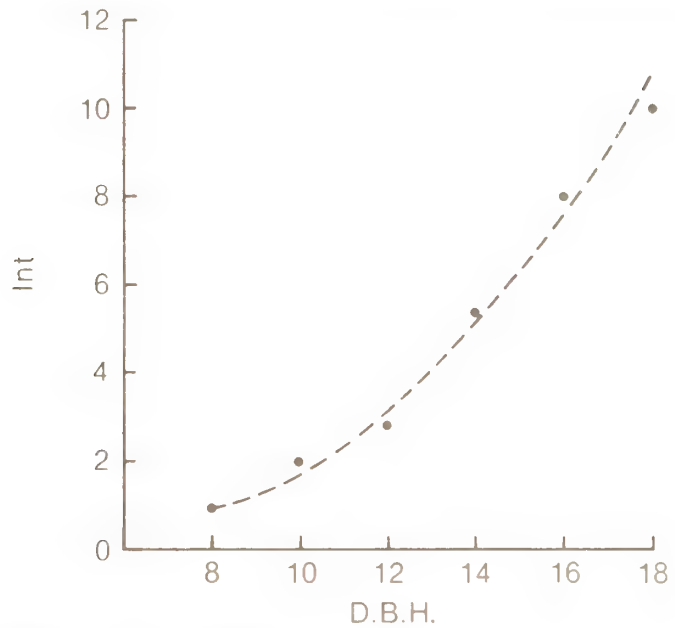


Figure 64.—*Int* smoothed.

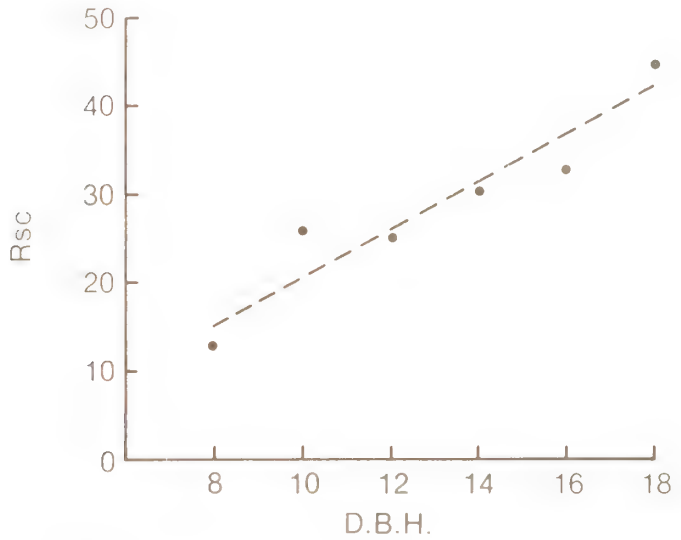


Figure 65.—*Rsc* smoothed.

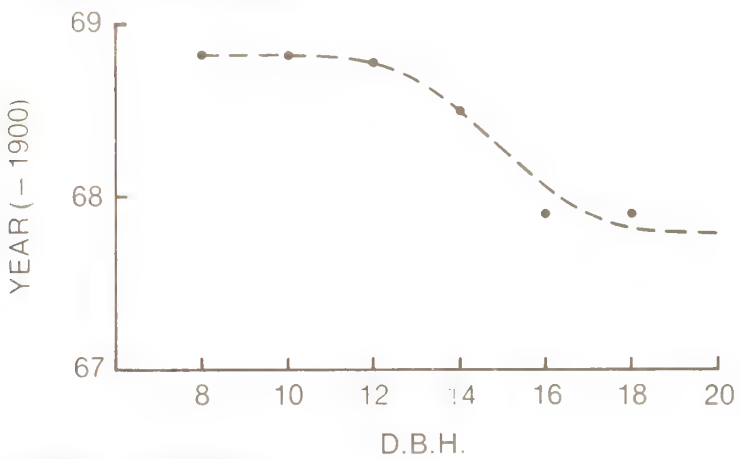


Figure 66.—*XP* smoothed.

found in the e^{-K}-Standards when the d.b.h. scale was reversed to 20-(d.b.h.).

Lsig specifies the sigmoidal shape of the left side (fig. 62). After transforming Year to $5-|Yr-XP|$ to create X-values ranging from zero at $XP-5$ to 5 at XP, the six d.b.h. group cross sections (left halves) were each scaled to 1.0 in X and Y at critical points in X. Overlay curves were plotted for these cross sections (fig. 67). The pattern was one of wider sigmoidal crowns near d.b.h. = 14 inches, narrowing with departure from that d.b.h. This is reflected in the bell-shaped function for the inflection points, *LI*. Also, the e^{-K}-Standards with $n = 1.5$ were found to represent this curve array with reasonable accuracy, so *Ln* was set at the constant, 1.5.

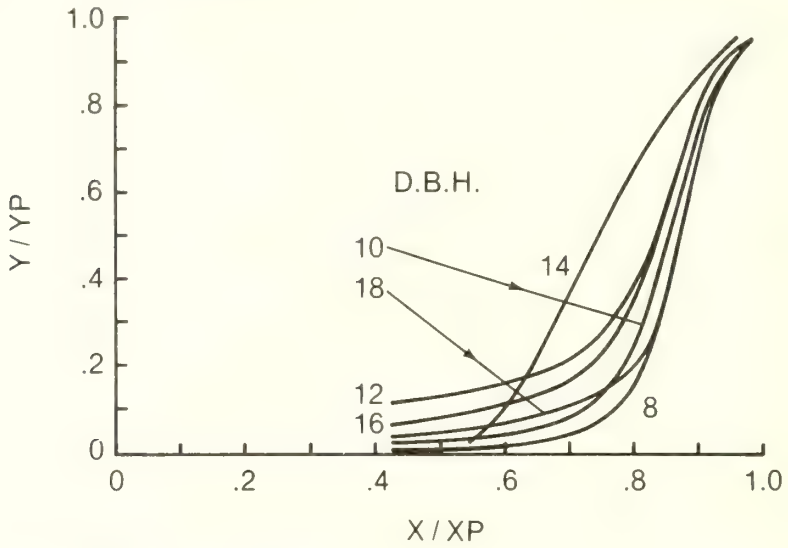


Figure 67.—The overlay curves.

LI, the function for the inflection points, is the dashed line in figure 68 and represents the inflection points adopted and plotted for each overlay curve. *LI* reflects the width-of-curve-crown trend noted under *Lsig* and in the text.

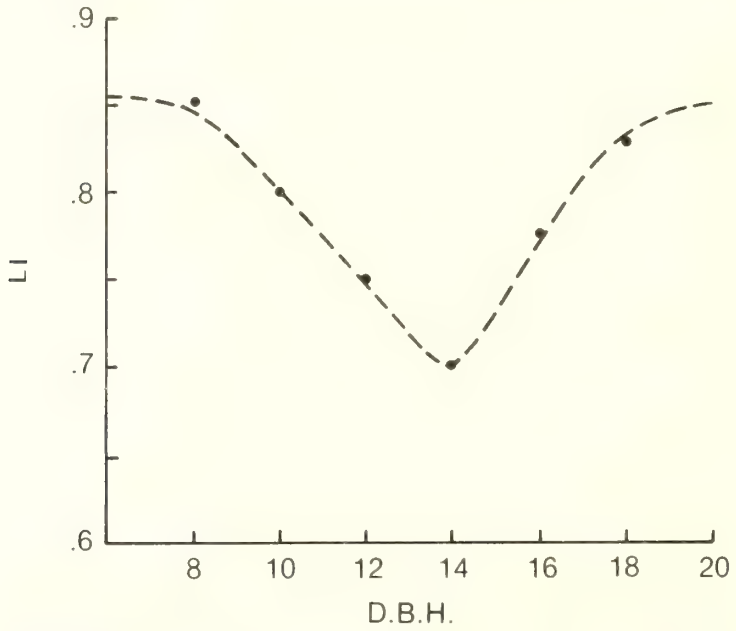


Figure 68.—*LI* smoothed.

Rsig, ***RI***, and ***RN*** were obtained in a similar fashion. The Year transform again was $5-|Yr-XP|$ and ranged in value from 5.0 at XP to zero at $XP+5$. The right-side cross sections were fairly well matched by e^{-K}-Standards with $n=2$, so Rn was set constant at $Rn=2$. RI showed the same general widening of curve crown at d.b.h. = 14 inches.

Asymmetrical Bell-Shaped Ridge over $X1$, with Moving Peak in $X2$. This is described in Three Segments and Interacts with a Sigmoidal $X2$-Effect

Live Data Example

Quality score (t) was originally described as an aggregate of 11 planar regions over flow (F) and stability (S) of gap-graded road materials, a strongly segmented descriptor (fig. 69, from Lee and others 1973). The objective here was to smooth the figure mathematically. Although the problem is an unusual one, its solution serves admirably to demonstrate descriptor segmentation.

From figure 69, it can be seen that opposite sides of the ridge differ substantially in slope so that an symmetrical, flat-topped, bell-shaped curve would be required to describe the cross section at any point in S while rounding the junctures of planes. A relatively simple descriptor alternative involves segmentation of the (S) and (F) regions as shown, with left and right orientation lines. Note that the lines are parallel to their respective sides of the ridge and lie one unit in F closer to the ridge center. This permits use of a single, but different, sigmoid cross section to represent and smooth the corners of each segment, left and right. The sigmoids will peak at their respective orientation lines and will be functional over a constant distance from them (left or right as appropriate). The constant will vary by side as needed. Since the ridge is flat topped, it will have a value of $t=10$ everywhere in the center segment.

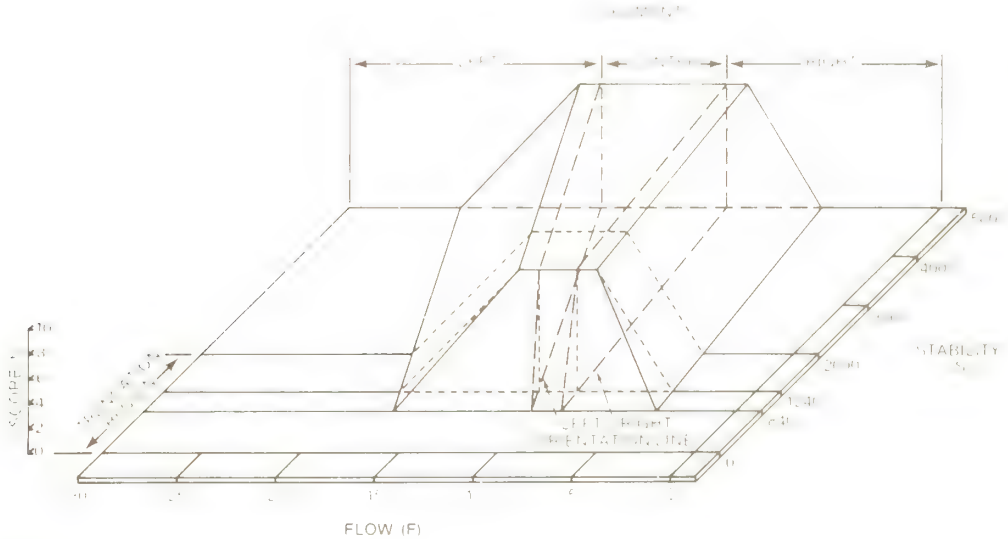


Figure 69.—Quality of gap-graded road materials: segmented planar form.

Then, to this point, we have described a ridge with three segments specified in terms of S and F; the sigmoidal effect to the left of the left orientation line; the sigmoidal effect to the right of the right orientation line; and the flat ridge area between these lines at a value of $t = 10$.

Finally, a sigmoidal truncation of the front end of this ridge is achieved through multiplication of all components of the descriptor by an appropriate sigmoid, changing in value from zero to one within the range $0 \leq S \leq 2000$, and being applicable for $0 \leq S \leq 5000$.

In general terms, we have:

$Lsig$ and $Rsig$ = left- and right-segment sigmoids, respectively
LO, RO = left- and right-orientation lines, respectively
CC = center segment, constant
$Tsig$ = truncator sigmoid

Then

$$t = Tsig(Lsig + CC + Rsig)$$

and

$$Tsig = f(S)$$
$$Lsig = f(LO,F)$$
$$Rsig = f(RO,F)$$
$$LO = f(S)$$
$$RO = f(S)$$

Limits

For $Lsig$, $LO < F \leq 28$
For $Rsig$, $0 \leq F \leq RO$
For CC, $LO \leq F \leq RO$
and, $0 \leq S \leq 5000$.

The final descriptor form is shown in figure 70 along with the original planar form for comparison. It can be seen that the descriptor does a creditable job of emulating the planar form while smoothing the corners, all with three segments in place of the original 11 segments.

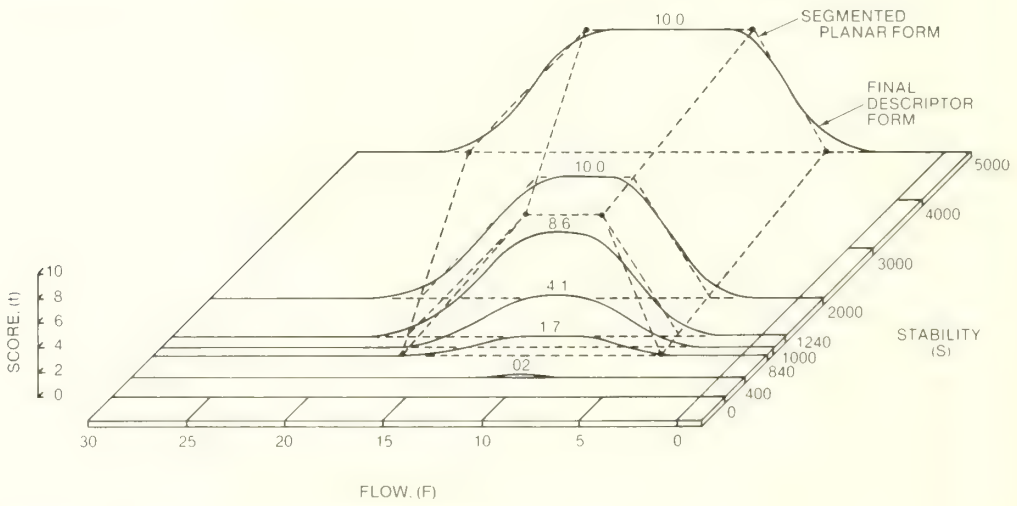


Figure 70.—Quality of gap-graded road materials: segmented planar and final descriptor forms.

Explicit hypothesis and moderate developmental detail follow:

If

$$F > LO,\ t = Tsig(Lsig)$$
$$LO \le F \le RO,\ t = 1.0(Tsig)$$
$$F < RO,\ t = Tsig(Rsig)$$

where

F = soil flow
$LO = 8.888 + 0.0017036(S)$
$RO = 8.404 + 0.0004807\,6(S)$
S = soil stability

$$Lsig = 10e^{-\left|\frac{(LO + 20 - F)}{20} - 1\right|^{2.5}}$$

$$Tsig = 1 - e^{-\left|\frac{(6000 - S)}{6000} - 1\right|^{6}}$$

$$Rsig = 10e^{-\left|\frac{|RO - 11| + F}{11} - 1\right|^{2.4}}$$

Limits

$0 \le F \le 28$,
$0 \le S \le 5000$.

Supplementary Explanatory Detail

Lsig, the left segment of figure 69, has a constant cross section over F for $1240 \le S \le 5000$, approximated in the descriptor by a sigmoid oriented at $F = LO$ and extending leftward a distance of 20 units in F. This is about the minimum operational span for the sigmoids here. At the upper extreme of S, ($S = 5000$), the left-segment sigmoid is expected to be completely specified in the range $27 \ge F \ge LO$, as in figure 70. Setting 28 as the upper level of F within which all left-segment sigmoids must be completely specified, we turn to the limiting case at $S = 0$. Here, $LO = 8.888$ and the sigmoidal range must then be at least $(28 - 8.888) = 19.112$; so 20 was adopted as the operational span. Note that a larger span could have been adopted.

The F-scale is reversed to $(LO + 20 - F)$, as shown in figure 71, to associate the largest value of the sigmoidal span, 20, with the peak of the sigmoid at LO. By scaling control points from the left cross section at $S = 1240$ (fig. 71) to 1.0 in X, $(LO + 20 - F)$, and Y, (score, t), and making an overlay curve, an appropriate sigmoid was identified from the e^{-K}-Standards.

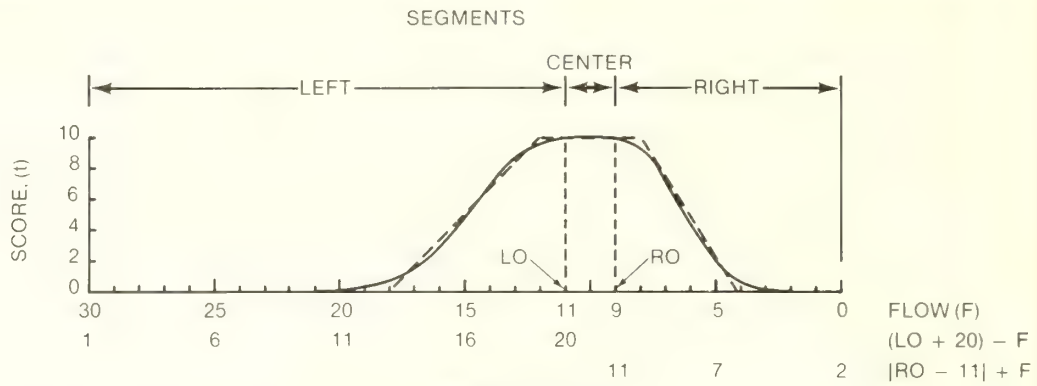


Figure 71.—A *t*-cross section over *F* at *S* = 5000. Note: the cross-sectional shape of the left segment is constant in the range 1240 ≤ *S* ≤ 5000; the right segment, although different in cross-sectional shape, is also constant in shape over the range 1240 ≤ *S* ≤ 5000.

Tsig, from (fig. 72), the planar ridge truncation ranges from $t = 0$ at $S = 840$ to $t = 10$ at $S = 1240$. This plane, scaled to 1.0, is matched and smoothed by *Tsig*, as is shown in figure 72. Note from the explicit *Tsig* formula that the inverted sigmoid to the left of the truncation plane (with base = 1.0 and peaking at 0, 0) was described on the reversed *S*-axis, $(6000 - S)$, and subtracted from 1.0 to arrive at *Tsig*. This provided a more accurate duplication of the truncator plane than did other sigmoid alternatives in this case.

Although a maximum of $S = 6000$ appears in *Tsig*, the applicable range is still limited to $S = 5000$ based on the original figure (fig. 69).

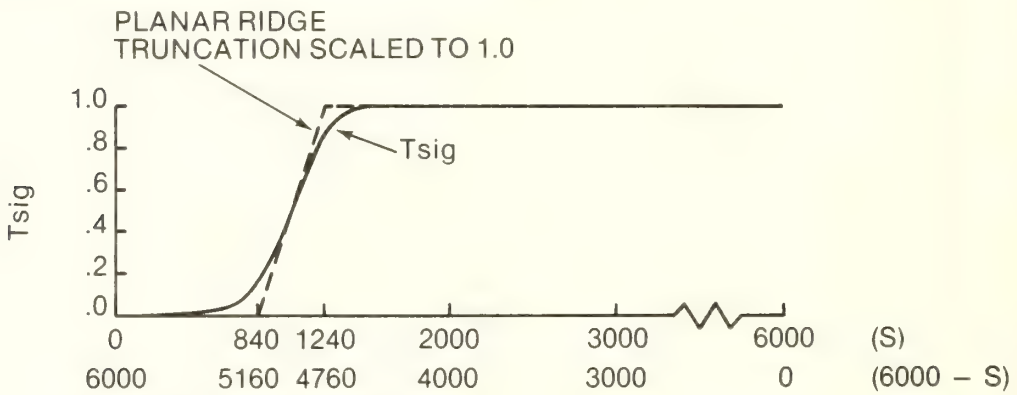


Figure 72.—Ridge truncation sigmoid, *Tsig*.

Rsig, the right segment of figure 69, has a constant cross section over *F* for $1240 \leq S \leq 5000$, approximated in the descriptor by a sigmoid oriented at *RO* and extending to the right for a distance of 11 units in *F*. Eleven is about the minimum operational span for the right-segment sigmoids. *RO* ranges from 8.404 at $S = 0$ to 10.808 at $S = 5000$. A range of 11 includes $F =$ zero at both extremes and so was adopted. The *Rsigs* were described as a function of the *F*-transform $|RO - 11| + F$, as shown in figure 71. Thus, the maximum value of 11 always occurred at the sigmoidal peak, $F = RO$, and *Rsig* functioned over the range zero to 11 of the *F*-transform.

Summary

The final surface, then, is simply the sum of the three contiguous ridge segments, all of which are truncated at appropriate points in *S* through multiplication by the proportional values of *Tsig*.

Symmetrical, Inverse Bell-Shaped Ridge over $X1$, with Constant Point of Minimum in $X1$ and Interacting with a Concave-Upward $X2$-Effect

Live Data Example

Here, the amount of natural reproduction (number of lodgepole pine seedlings per acre) over the Sleeping Child burn was expected to be affected by both azimuth and slope (data from Lyon 1976). Further, azimuth and slope were expected to interact strongly, the magnitude of response to azimuth being dependent on slope percent.

A small data set was used to develop a graphic hypothesis consistent with these expectations. It was very close to the mathematical hypothesis pictured in figure 73.

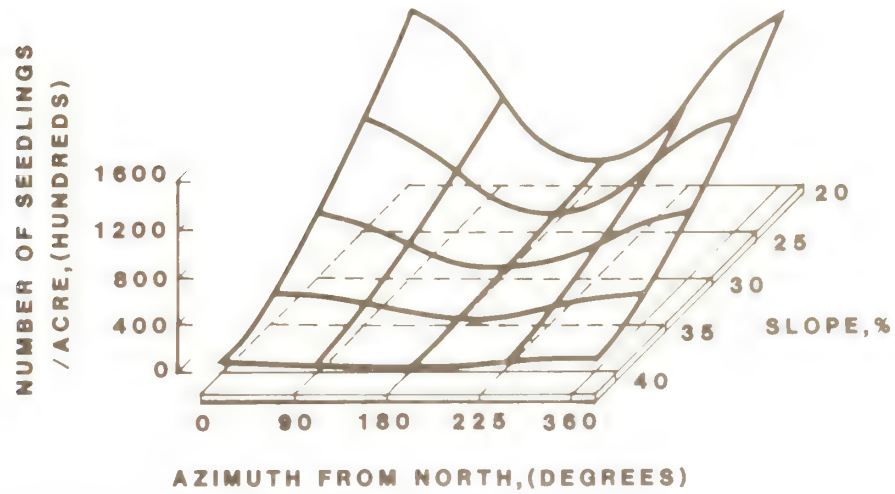


Figure 73.—The mathematical hypothesis.

Descriptor Development for Figure 73

The **Azimuth (A)-effect** may be seen as cross sections over AZ at slope percent (SL) = 20, 30, 35, and 35. These were screened for shape using the e^{-k}-Standards. Note that, since the bell-shaped curves were symmetrical, either sigmoidal half would be representative of the whole (the left-half was used). Also, negative departures from either edge could be used to specify the depth of the sigmoids (these negative values were ignored in the screening, but were accounted for in the final mathematical hypothesis). Sigmoids were found to be sufficiently similar at different SL-levels to adopt the common form,

$$e^{-k} = 1.0675 * e^{-\left|\frac{AZ}{180} - 1\right|^{2.4}} - 0.0675,$$

where the trough is at a fixed point in AZ (XP = 180, here).

And, given the subtraction of suitably scaled sigmoids from either edge (*EDGE*),

$$\text{Number of seedlings} = \text{EDGE} - YP(1.0675^{*}e^{-\left|\frac{\frac{AZ}{180}-1}{0.655}\right|^{2.4}} - 0.0675),$$

where *EDGE*, was better matched by the lower 85 percent of a sigmoid on the reversed slope scale with a maximum value of 100 than by a simple X^n-form. Thus,

$$\text{EDGE} = 2400^{*}e^{-\left|\frac{\frac{(100-SL)}{100}-1}{0.255}\right|^{2.6}}.$$

The trough of the objective figure (*MIN*) was expressed as the height of the negative bell-shaped (or sigmoidal) peaks above the 3-D base. As with *EDGE*, this was described as the lower 85 percent of a sigmoid on the reversed slope scale with a maximum value of 100. And,

$$\text{MIN} = 250^{*}e^{-\left|\frac{\frac{(100-SL)}{100}-1}{0.29}\right|^{2.3}}.$$

Then, $YP = \text{EDGE} - \text{MIN}$

LIMITS: $0 \le AZ \le 360$, $20 \le \text{SLOPE} \le 45$.

Note that inverse asymmetrical bell-shaped functions, often typical of azimuth effects on plant growth, can be described roughly as above, but in two segments. Each segment then has its own sigmoidal shape. Also, it could easily be that the trough, which was at a fixed point in AZ ($XP = 180$), in the foregoing example, changes in AZ depending on slope. In such a case, $XP = f(SL)$ in the sigmoidal effect of AZ.

Concave-Upward Relation in Two Dimensions, with Constant Point of Peaking in $X1$ Over X2.

Live Data Example

Soil temperatures (ST) at various depths and percent of duff reduction were studied on a clearcut area that had been subjected to a controlled burn. A data set (from Shearer 1974 and 1975) was devoted to hypothesis development as shown below.

Data were grouped into duff-reduction (DR) classes and trends over "depth in soil" (DS) were smoothed in accord with expectation. These were screened over the reversed DS-scale in the X^n-Standards and were all reasonably represented by $b_1(7 - DS)^6$.
Then,

$ST = 45 + (YP/(7)^6)(7 - DS)^6$.

And, YP, the smoothed curve of scaling heights for the individual DS-curves (at the scaling point $[7 - DS] = 7$), was concave-upward over DR and could have been described as an exponential function of DR. The lower half of a sigmoid, however, was found to mimic the objective curve more closely so,

$$YP = 365.171(e^{-0.56\left(\frac{DR}{200}-1\right)^{2.2}}) - 10.171,$$

thus producing figure 74. Limits of use for this hypothesis are: $0 \leq DR \leq 100$ and $0 \leq DS \leq 7$.

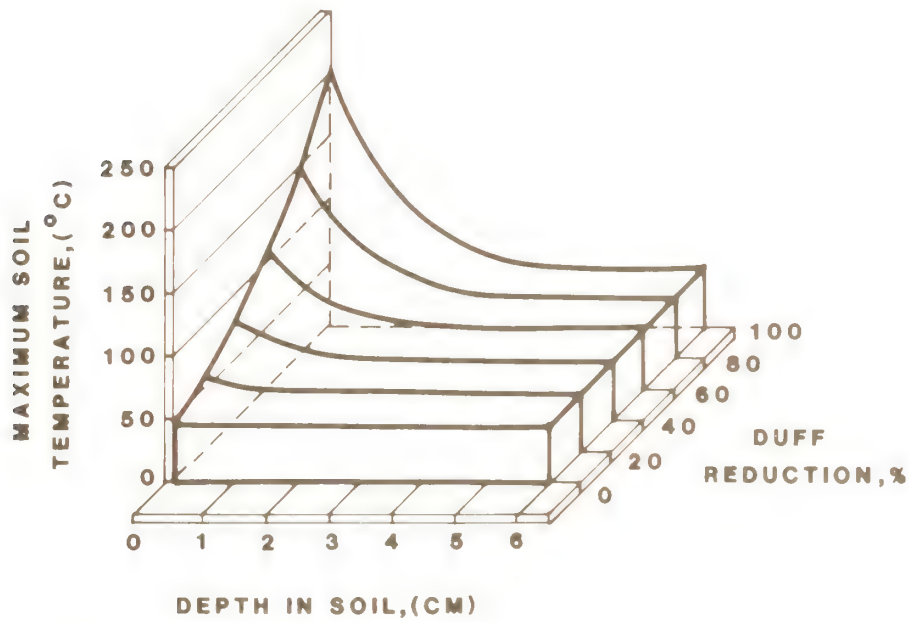


Figure 74.—The mathematical hypothesis.

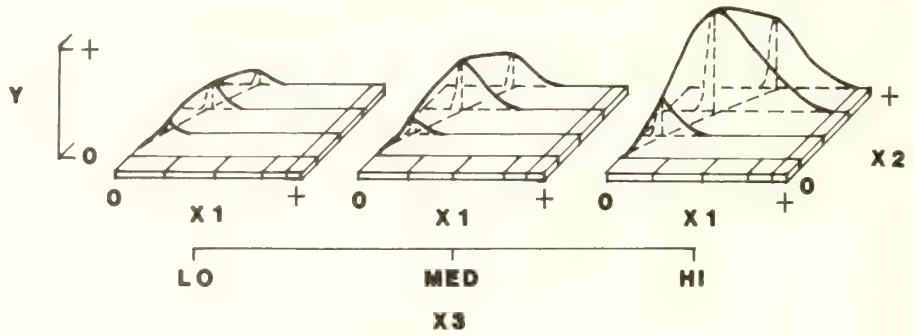
Note that only the lower (left) half of the YP-sigmoid is utilized in this relation as the result of doubling the DR-scale ($XP = 200$) and the ST scale as well (YP + intercept = 400, or $YP = 355$). In the last case, it would have been more consistent to have used $YP = 400$, but a suitable e^{-K} was found with 355; so 355 was retained.

MATHEMATICAL DESCRIPTION OF GRAPHED HYPOTHESES – FOUR DIMENSIONS

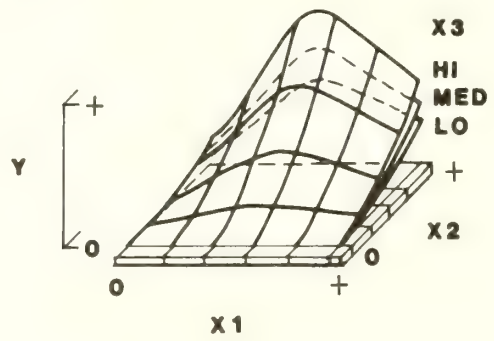
Outline for "FOUR DIMENSIONS"

PAGE

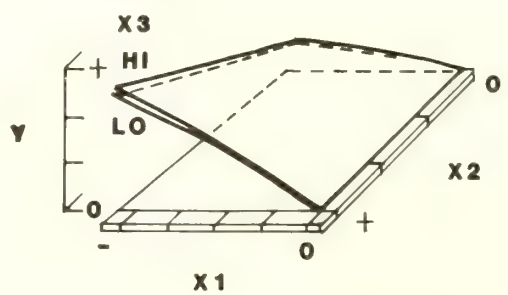
Asymmetrical Bell-Shaped *X*1-Effect with Point of Peaking Moving in *X*2. The *X*1-Effect is Described in Two Segments and Interacts with the Bell-Shaped *X*2-Effect and the Concave-Upward *X*3-Effect (Contrived Example) 78



Asymmetrical Bell-Shaped *X*1-Effect, with Constant Point of Peaking in *X*2. The *X*1-Effect is Described in Two Segments and Interacts with Concave-Upward *X*2- and *X*3-Effects (Live Data Example) 83



Convex-Upward *X*1-Effect with Peak Moving in *X*2, Interacting with Concave-Upward *X*2-Effects and Slight Convex-Upward *X*3-Effects (Live Data Example) 86



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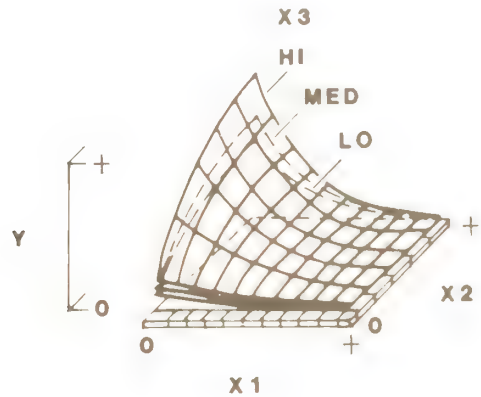
Concave-Upward *X*1-Effects, with Constant Point of Peaking in *X*2 and Interacting with Convex-Upward *X*2-Effects; Fourth Dimension Discrete (Live Data Example) 90



Asymmetrical Bell-Shaped *X*1-Effect with Point of Peaking Moving in X2. The *X*1-Effect is Described in Two Segments and Interacts with the Bell-Shaped *X*2-Effect and the Concave-Upward *X*3-Effect

Contrived Example

Assume that finite curve forms and scales for a 4-D relation have been developed (within gross constraints of the expected relation) from trend information contained in half of a current data set, partitioned over the ranges of the three independent variables. The most prominent feature of the resulting curve array is the asymmetric nature of the *X*1-effect. This is displayed in figure 75 at three levels of *X*2, within each of three levels of *X*3.

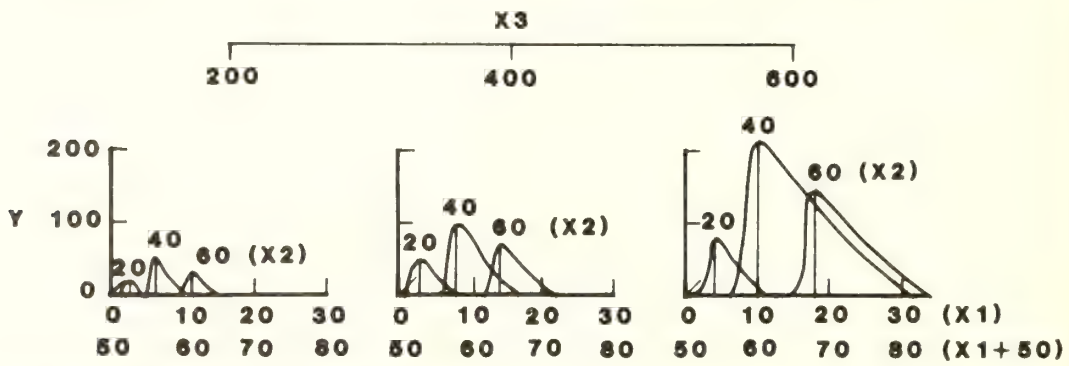


Figure 75.—The partial graphed hypothesis.

Also prominent, is the *X*2-effect, bell shaped, but truncated at the high end of the *X*2 scale. This is perhaps more fully appreciated in figure 76.

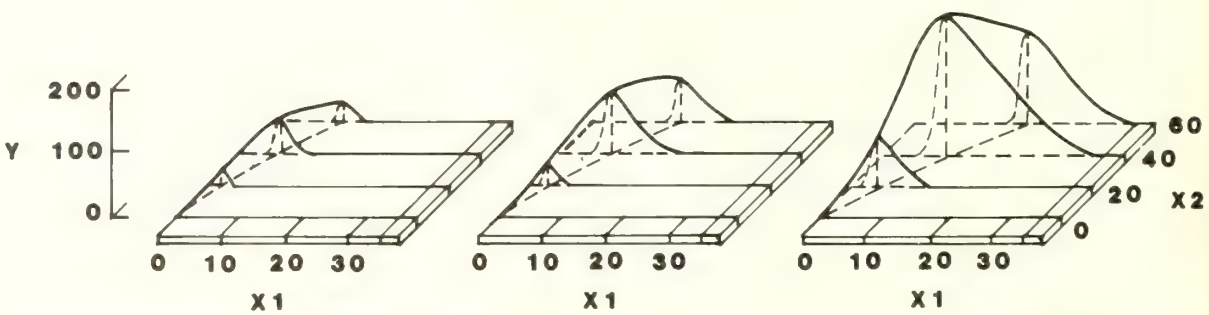


Figure 76.—The complete graphed hypothesis.

The number of *X*2- and *X*3-partitions are kept to a minimum to simplify the presentation of associated descriptive methods. More partitions would probably be desirable in a live data application.

Descriptor methods involved are identical to those shown earlier for 2- and 3-D hypotheses and are simply expanded to accommodate another independent variable. From figure 76 we can anticipate a reasonable mathematical hypothesis to be as shown below.

***X1*-Effect.**—Since the bell-shaped curves are asymmetric, it would be efficient to create a sigmoidal descriptor for the left and right sides separately. They would be joined at $XP1$ and would be scaled to a common height, $YP1$. Thus, with $X1$ adjusted to $X1 + 50$ to accommodate the curve-breadth limit, $XP \pm XP$, the hypothesis for say, the left half, would be:

$$YL = YP1(e^{\wedge}) \text{ left}$$

or,

$$YL = YP1 \left\{ \frac{e^{\left(\frac{(X1+50)}{XP1}\right)^{\frac{1}{IL}}} - e^{\left(\frac{1}{1-IL}\right)^{\frac{1}{IL}}}}{1 - e^{\left(\frac{1}{1-IL}\right)^{\frac{1}{IL}}}} \right\}$$

where $YP1$, $XP1$, IL, and nL may change over the range of $X2$, $X3$, or both.

***YP1*.**—Plotting the heights of the nine curves from figure 76 in figure 77 and smoothing over these points, $YP1$ varies as a symmetrical bell-shaped curve ($e_2^{\wedge}$) over $X2$, changes in height ($YP2$), and perhaps changes in shape (n and I) over $X3$. Then, $YP1 = YP2(e_2^{\wedge})$.

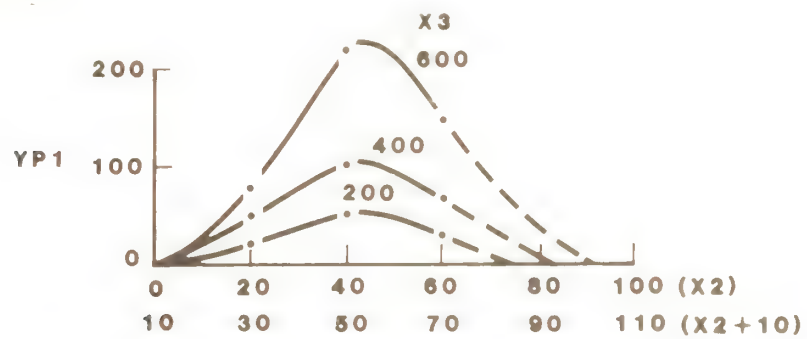


Figure 77.—YP1 smoothed.

***YP2*.**—From figure 78, the plotted heights of these curves appear to follow an exponential function of X. Let us assume that we have made and compared an overlay curve with the X^n-Standards and that we have found a suitable descriptor in $YP2 = b_3(X3)^{n3}$.

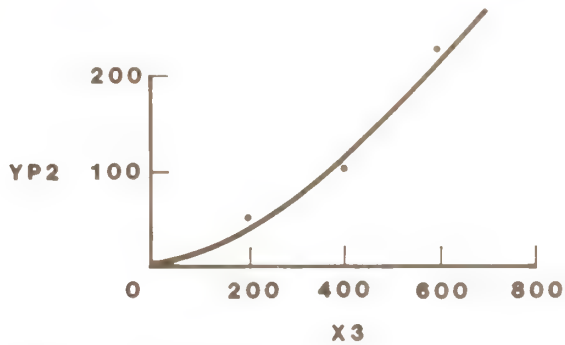


Figure 78.—YP2 smoothed.

***X2* in e_2^{-K}.**—The largest sigmoid of the set (for $X3 = 600$) reaches $X2 = 90$. Since $XP2 = 45$ here, all sigmoids fall within the required limits, $XP \pm XP$. But, it might be reasonable to extrapolate to $X3 = 700$ where the expected maximum might be say 100. In which case, a constant can be added to $X2$ in e^{-K} to accommodate the $(XP \pm XP)$-requirement, using $(X2 + 10)$ in place of $X2$, $XP2 = 55$, and $2XP2 = 110$. Then, the broadest curve will fall within $XP2 \pm XP2$.

***XP2* in e_2^{-K}.**—As may be seen in figure 77, $\hat{XP2} = 45$ in $X2$ for all levels of $X3$. And, since $(X2 + 10)$ is to be used in place of $X2$, $\hat{XP2} = 55$.

***n_2* in e_2^{-K}.**—Assume that overlay curves have been made for the left half of the three symmetrical bell-shaped curves in figure 77 and that comparison with the e^{-K}-Standards resulted in $n = 1.7$, 2.0, and 2.5 for $X3 = 200$, 400, and 600, respectively. Without the formality of plotting, n_2 will be assumed to be an exponential function of $X3$ so that: $\hat{n}_2 = a_4 + b_4(X3)^{n4}$.

***I_2* in e_2^{-K}.**—Along with n_2, above, assume that appropriate I_2-values have been identified as 0.50, 0.45, and 0.40 for $X3 = 200$, 400, and 600, respectively. By inspection, I_2 is a negative linear function of $X3$ so that $\hat{I}_2 = a_5 - b_5(X3)$.

In summary,

$$\hat{YP1} = YP2 \left\{ \frac{e^{-\left|\frac{(X2+10)}{XP2} - 1\right|^{n_2}} - e^{-\left\{\frac{1}{1-I_2}\right\}^{n_2}}}{1 - e^{-\left\{\frac{1}{1-I_2}\right\}^{n_2}}} \right\}$$

where,

$\hat{YP2} = b_3(X3)^{n3}$

$\hat{XP2} = 55$

$\hat{n}_2 = a_4 + b_4(X3)^{n4}$

$\hat{I}_2 = a_5 + b_5(X3)$.

***X1* in $(e^{-K})_{left}$.**—Revision of $X1$ is necessary, since the smallest XP (from figure 76) approaches zero and the broadest curve reaches $X1 = 35$ at $X3 = 600$. Assuming extrapolation to $X3 = 700$, we might expect the broadest curve to reach no more than say $X3 = 50$.

To meet the constraint that all curves of the set be within $XP \pm XP$, $(X1 + 50)$ was used in place of $X1$. Then, where $XP1 = $ zero, $(X1 \pm 50) = 50$ and, at the high extreme where $X1 = 35$, $(X1 + 50) = 85$. And, using $(X1 + 50)$ in e^{-K}, all curves will be within the minimum $XP1 = 50$, since $\pm 2XP1 = 100$.

***XP1* in $(e^{-K})_{left}$.**—$XP1$-values read from figure 76 are plotted and smoothed in figure 79.

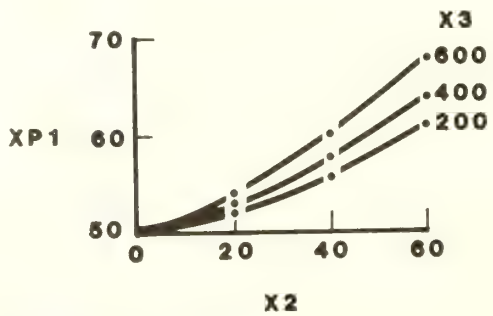


Figure 79.—*XP1* smoothed.

We will assume by inspection, that $XP1$ is an exponential function of $X2$ and that

$$XP1 = (YP3/(60)^{n6}(X2)^{n6}.$$

YP3.—At the scaling point, $X2 = 60$, the heights ($YP3$) of the three curves in figure 77 are read as 11, 14, and 18, for $X3 = 200$, 400, and 600, respectively. Plotting these points in figure 80 and smoothing, $YP3$ can be seen to be a very flat exponential function of $X3$ so that

$$YP3 = a + b_7(X3)^{n7}.$$

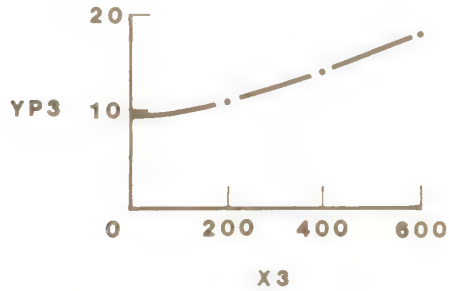


Figure 80.—YP3 smoothed.

Also, we will assume that the shapes of the three curves in figure 77 have been compared with the X^n-Standards and have been found to have a constant n.

Then, $XP1 = (YP3/(60)^{n6})(X2)^{n6}$
where $YP3 = a_7 + b_7(X3)^{n7}$.

***nL* and *H* in $(e^{\wedge})_{left}$.**—We will assume that the left sides of the nine curves in figure 75 have been screened for matching $e^{\wedge}$-Standards with the results shown in tables 27 and 28.

Table 27.—*nL* in $(e^{\wedge})_{left}$

X2	X3		
	200	400	600
	n		
20	2	2	2
40	2	2	2
60	2	2	2

Table 28.—*IL* in $(e^{-K})_{left}$

X2	X3		
	200	400	600
	---------- *IL* ----------		
20	0.970	0.965	0.938
40	.965	.959	.943
60	.973	.955	.940
average	0.969	0.960	0.940

nL.—Referring to table 27, the set of e^{-K}-Standards with $n = 2$ was deemed appropriate for the set, all levels of $X2$ and $X3$ included. So, $NL = 2$, a constant.

IL.—The *I*-values in table 28 are quite large since the left-side curves have very steep slopes and are proportionally far to the right in the $(X1 + 50)$ range. Systematic variation is associated primarily with changes in $X3$ as indicated by the average *IL*-values. These are plotted and smoothed in figure 81.

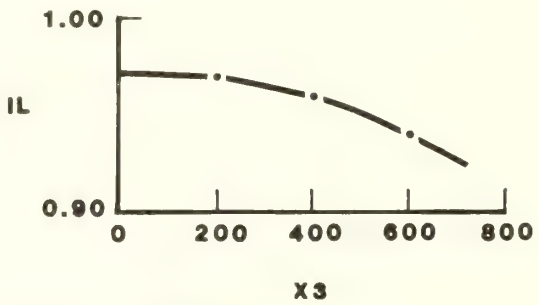


Figure 81.—*IL* smoothed.

And, again assuming this relation can be satisfactorily expressed by an exponential, we have:

$$\hat{IL} = 0.971 - b_7(X3)^{n7}.$$

Then, to summarize, the entire left side of the hypothesis may be specified as:

$$\hat{YL} = YP1(e^{-K}) \text{ left}$$

or,

$$\hat{YL} = YP1 \left\{ \frac{e^{-\left|\frac{(X1+50)}{XP1} - 1\right|^{nL}} - e^{-\left\{\frac{1}{1-IL}\right\}^{nL}}}{1 - e^{-\left\{\frac{1}{1-IL}\right\}^{nL}}} \right\}$$

where $YP1$, $XP1$, IL, and nL may change over the range of $X2$, $X3$, or both.

$$\hat{YP1} = YP2\left\{\frac{e^{-\left|\frac{(X2+10)}{XP2}-1\right|^{n_2}\Big/\left(1-I_2\right)} - e^{-\left\{\frac{1}{1-I_2}\right\}^{n_2}}}{1-e^{-\left\{\frac{1}{1-I_2}\right\}^{n_2}}}\right\}$$

and

$YP2 = b_3(X3)^{n3}$
$XP2 = 55$
$n_2 = a_4 + b_4(X3)^{n4}$
$I_2 = a_5 + b_5(X3)$
$XP1 = (YP3/(60)^{n6})(X2)^{n6}$ and
$YP3 = a_7 + b_7(X3)^{n7}$
$nL = 2$
$IL = 0.971 - b_8(X3)^{n8}$.

Description of the right side of the hypothesis would be approached in the same fashion as above, to provide the unknowns in:

$$\hat{YR} = YP1\left\{\frac{e^{-\left|\frac{X}{XP1}-1\right|^{nR}\Big/\left(1-IR\right)} - e^{-\left\{\frac{1}{1-IR}\right\}^{nR}}}{1-e^{-\left\{\frac{1}{1-IR}\right\}^{nR}}}\right\}.$$

Note that $X1$ for the right side curves could be set $= (50 - X1)$ and $YP1$ and $XP1$ are the same for the right side as for the left.

Asymmetrical Bell-Shaped $X1$-Effect, with Constant Point of Peaking in X2. The $X1$-Effect is Described in Two Segments and Interacts with Concave-Upward $X2$- and $X3$-Effects

Live Data Example

The relation between total terpene content of lodgepole pine phloem by d.b.h. (D) phloem thickness (P), and 5-year radial growth (G) (from W. E. Cole and others 1981) was hypothesized graphically very nearly as in figure 82.

In explaining descriptor development here, we will focus on generalities. The details of formulating the graphed hypothesis, selecting control points, making overlay curves and comparing them to the Standards are assumed to be known from earlier text.

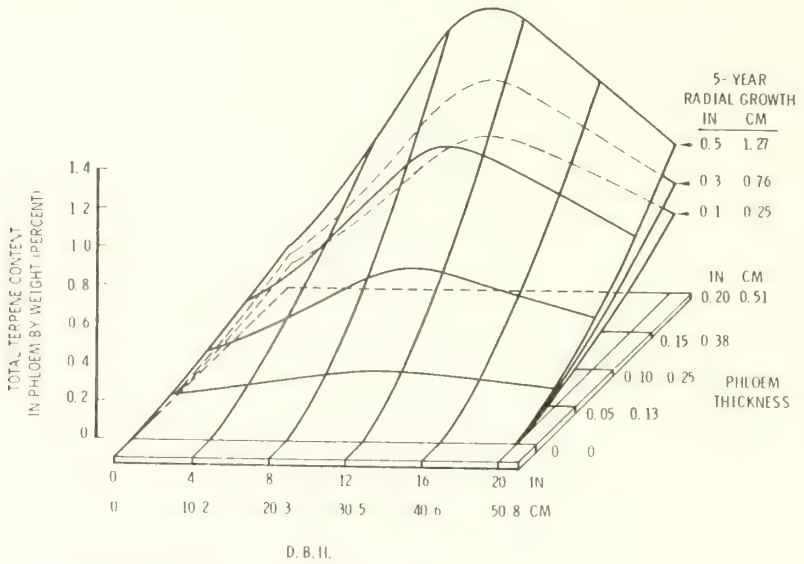


Figure 82.—The mathematical hypothesis.

In this example, the phloem thickness (P) effect was strong in both expectation and data trends (after testing more modest hypotheses, a data set was exploited for interactive hypothesis development). Its effect in the data was clearly exponential within d.b.h./growth data groups and appeared to be reasonably constant at about $n = 1.55$. Then, where the scaling point in P was at $G = 0.14$ (the approximate upper limit of the data over G),

$$\text{percent terpene content} = \left\{ \frac{YPP}{(0.14)^{1.55}} \right\} p^{1.55} .$$

The heights of the peaks (YPP) of the asymmetrical bell-shaped curves over d.b.h. (D), at the constant point of peaking (XP), 10.5 inches, are specified as:

for $D \leq 10.5$

$$YPP = YPD\left(1.00165\, e^{-\left|\frac{\frac{D+8.5}{19} - 1}{0.395}\right|^{2}} - 0.00165\right),$$

for $D > 10.5$

$$YPP = YPD\left(1.07092\, e^{-\left|\frac{\frac{38.5-D}{28} - 1}{0.490}\right|^{1.4}} - 0.07092\right),$$

where

$$YPD = 0.38 + 1.0292(G)^{1.4}.$$

Note that sigmoids over D, while having a different shape on opposite sides of the peak, were identified as having consistent shapes for the three growth levels.

This completes the formulation applicable in the range $0 \leq P \leq 0.20$, $0 \leq D \leq 25$, and $0 \leq G \leq 0.35$, but explanation of the D-transforms for the sigmoids may be helpful here. The broadest bell-shaped curve expected (at $P = 0.20$) ranges from about $D = -8.5$ on the left side to $D = 38.5$ on the right. With $XP = 10.5$, the D scale for the left side is changed to $(D + 8.5)$ and that for the right is $(38.5 - D)$, as shown in figures 83 and 84.

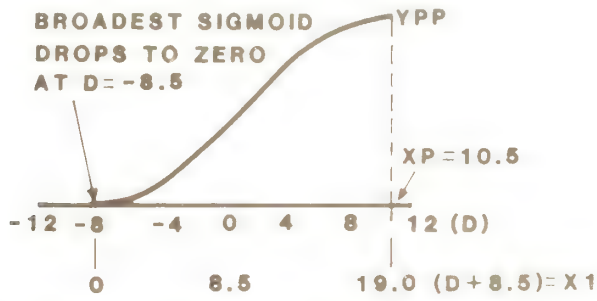


Figure 83.—D-transform for the left side.

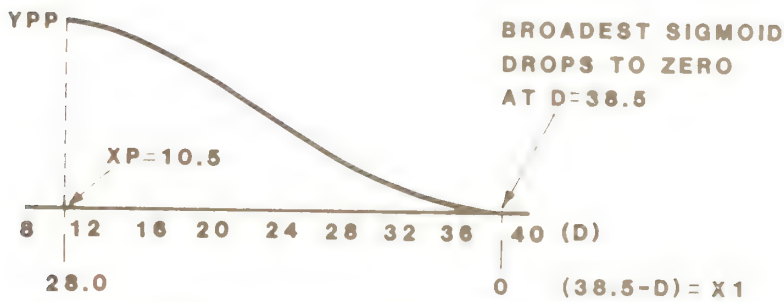


Figure 84.—D-transform for the right side.

Again, these transforms of D insure that all points of the sigmoids are within the range $XP1 \pm XP1$.

The foregoing hypothesis was ultimately refitted to the data from which it was largely derived. This provided the most realistic appraisal of scale available at the moment for the relation characterized.

Given that total terpene estimated from the model = X and that terpene content actually measured in the data = Y, the least squares coefficient, b, was

$$b = \Sigma XY / \Sigma X^2 = 1.10301.$$

This corrects for underscaling in the hypothesis insofar as the data set utilized is concerned. Slight improvement in R^2 was noted for the interactive hypothesis over that for the simple additive model with only linear effects of D, P, and G: $R^2 = 0.39$ versus 0.35, respectively. So, no potentially great advantage of the interactive over the additive model appears to exist in this data set. But, the hypothesis still provides new insights for the area of interest that should be of value in planning new studies.

Convex-Upward $X1$-Effect with Peak Moving in $X2$, Interacting with Concave-Upward $X2$-Effects and Slight Convex-Upward $X3$-Effects

Live Data Example

Laboratory-controlled calibration data for Peltier thermocouple psychrometers were assembled by Brown and Bartos, 1981, and are shown smoothed over water potential in figure 85.

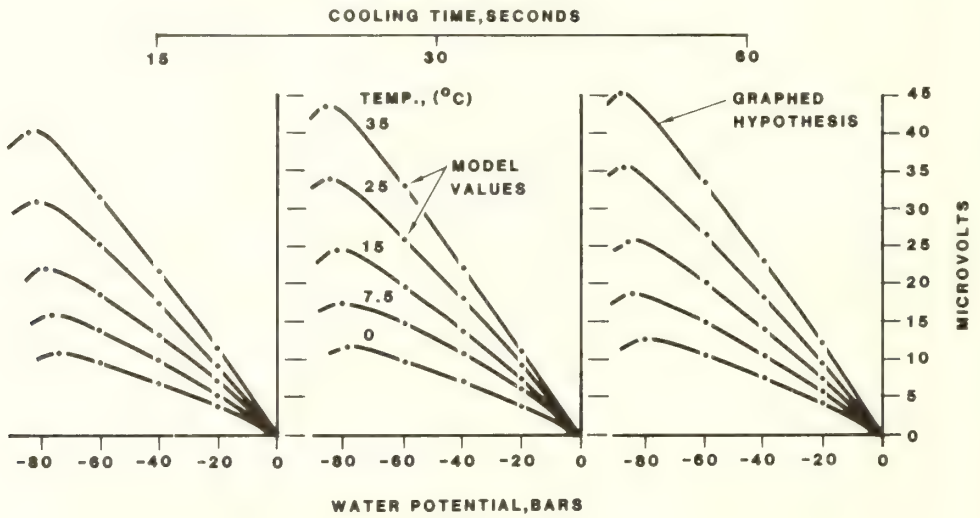


Figure 85.—The graphed hypothesis and model performance.

The combination of strong expectations for the relation, a well-conceived laboratory study, and strong data-group means left little doubt as to the form and scale of the relation between microvolt output and the independent variables, water potential in negative bars, temperature of the measured medium and the cooling time. The smoothed curves represent an exceedingly strong hypothesis and, with one additional variable, formed the basis for a published mathematical model intended for adjustment to other psychrometers of the same design. The four dimensional relation pictured, in fact, was described mathematically before including the effects of the fifth dimension and provides a unique opportunity to study four dimensional descriptor methods.

The strategy here was to describe microvolt output (MW) as a function of water potential (WP), temperature (T), and cooling time (CT), solving the resulting equation for (WP).

It was noted at the outset that interest in WP was limited to $XP \leq WP \leq 0$, where XP is the point in WP where microvolts peak. Also, it can be seen in figure 85 that XP changes over both T and CT. The heights of the curves, called upper intercepts (UI) here, change with both T and CT, and all curves over WP are oriented at zero.
The general form of the relation is estimable from figure 85 as:

$$MV = UI1 - (UI1/|XP|^{n1})|XP - WP|^{n1}.$$

This is an exponential in the reversed WP-scale, $|XP - WP|$, scaled to the difference between $UI1$ and zero ($= UI1$) at $WP =$ zero, and subtracted from $UI1$. Smoothed values of XP and $UI1$ were established and described first, since they were subsequently used in place of actual XP and $UI1$-values to smooth XP-effects.

XP.—Within each of the three cooling times, the negative XP-values were read from figure 85 for each of the five temperature curves. The absolute values of these were plotted and smoothed over T within CT-groups, with the results shown in figure 86 as

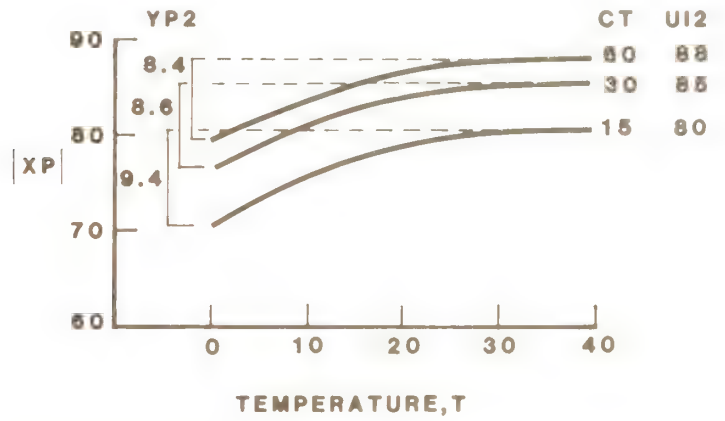


Figure 86.— XP, smoothed.

an exponential effect in the reversed T-scale, $(40 - T)$, scaled to the difference between an upper intercept ($UI2$), and scaled to the absolute difference between $UI2$ and the curve at $T =$ zero. Then, multiplying by (-1) to return $|XP|$ to its original negative state,

$$XP = (-1)(UI2 - YP2)(40)^{2.5})(40 - T)^{2.5}).$$

UI2.—The $UI2$-values were plotted over CT and smoothed as shown in figure 87.

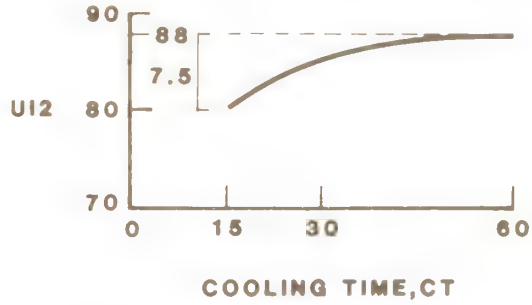


Figure 87.—$UI2$ smoothed.

This was described as an exponential in the reversed CT scale, $(60 - CT)$, subtracted from the upper intercept of 88.0, and scaled to the drop (7.5) at $CT = 15$. The resulting form was

$$UI2 = 88 - (7.5/(45)^{2.7})(60 - CT)^{2.7}$$
$$= 88 - 0.0002579\ (60 - CT)^{2.7}.$$

YP2.—Similarly, the $YP2$-values were plotted over CT and smoothed (fig. 88).

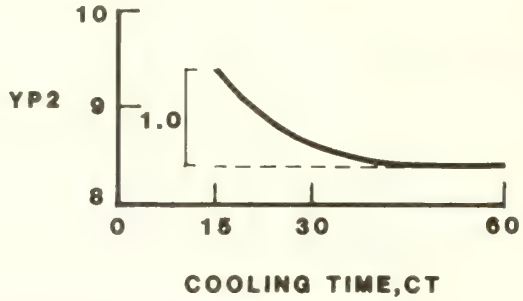


Figure 88.—*YP2* smoothed.

The resulting curve was described as an exponential in the reversed CT scale, $(60-CT)$, scaled to the difference, 1.0, from the intercept at $CT=15$, and added to the intercept. In this case,

$$YP2 = 8.4 + (1.0/(45)^{3.97})(60-CT)^{3.97}$$
$$= 8.4 + 2.734\times 10^{-7}(60-CT)^{3.97}.$$

The shapes of the curves over T in figure 86 were determined through overlay curves and the X^n-Standards to be virtually constant at $n_2 = 2.35$.
Then

$$XP = (-1)(UI2 - (YP2/(40)^{2.35})(40-T)^{2.35}).$$

*UI*1.—Following the analytical pattern for XT, peak values ($UI1$) of the 15 curves in figure 85 were read, plotted, and smoothed over T within each of three CT-groups. Comparison of overlay curves with the X^n-Standards led to adoption of a constant flat form ($n=1.1$) for all three curves. Intercepts and scaling heights changed over CT so that

$$UI1 = INT3 + (YP3/(40)^{1.1})(T)^{1.1}$$

where

$$INT3 = 12.1 - 0.003475(60-CT)^{1.63}$$
$$YP3 = 39.2 - 0.0004346(60-CT)^{2.45}.$$

n_1.—After graphically adjusting the figure 85 curves over WP for smoothed values of XP and $UI1$, absolute differences between the $UI1$ and the associated curves were read for seven points in WP ($XP \leq WP \leq$ zero). The resulting control points were normalized, plotted, and compared to the X^n-Standards. From this, n_1 varied sigmoidally over both T and CT such that

$$n_1 = 1.18 + 0.185\left\{\frac{e^{-\left|\frac{(40-T)}{40}-1\right|^m}_{1-I} - e^{-\left\{\frac{1}{1-I}\right\}^m}}{1-e^{-\left\{\frac{1}{1-I}\right\}^m}}\right\}$$

where

$$I = 0.45 + 0.000333(T) + (1.9846 \times 10^{-19})(CT)^{7}$$

$$m = 2.5 + e^{\frac{\frac{(60 - CT)}{60}}{0.405}}$$

So, with the foregoing inputs and as originally formulated,

$$MV = UM - (UM - XP^{m}) \left\{ \frac{XP^{m}(UM - MV)}{UM} \right\}^{1/m} + XP \Big\} * (-1), \quad XP \le WP \le 0.$$

can now be estimated with the foregoing inputs. Performance of the model is shown on figure 85 where it may be seen that the model is an excellent reproduction of the graphed hypothesis. Modest smoothing effects over CT exist near the peaks at 30 and 60 seconds. The resulting four dimensional model is presented in figure 89 at two points in the fourth dimension ($CT = 15,60$).

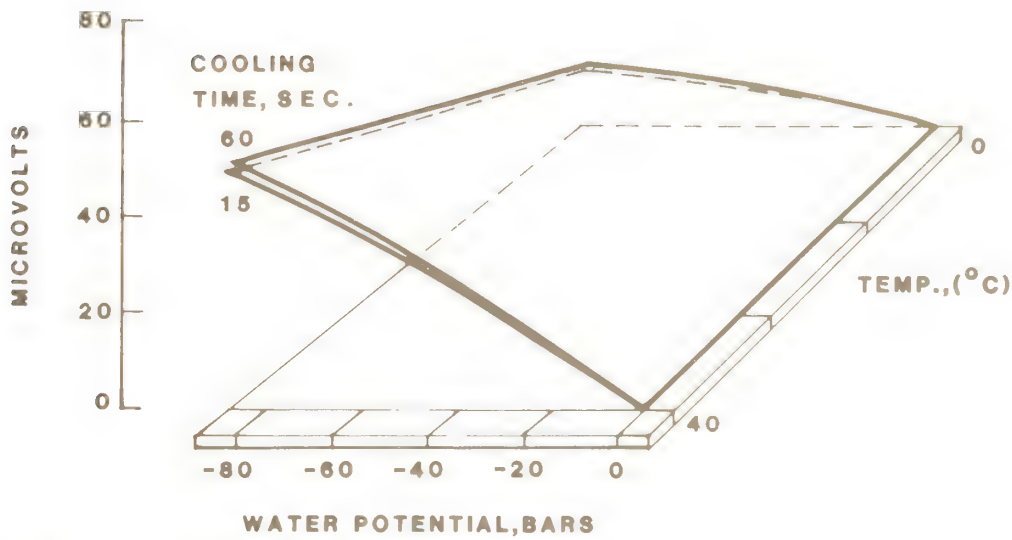


Figure 89.—The mathematical hypothesis for microvolts.

Solution for WP.—As stated previously, interest here focused on $WP = f(CT, T, \text{and } MV)$. Solving the MV estimator for WP, we have

$$WP = \left\{ \left\{ \frac{XP^{m}(UM - MV)}{UM} \right\}^{1/m} + XP \right\} * (-1), \quad XP \le WP \le 0.$$

Concave-Upward *X*1-Effects, with Constant Point of Peaking in *X*2 and Interacting with Convex-Upward *X*2-Effects; Fourth Dimension Discrete

Live Data Example

Here, phloem thickness (P) in lodgepole pine was expressed as a function of electrical resistance of cambium (R), d.b.h. (D) and of three discrete points in time, May, July, and October. The hypothesis (fig. 90) was based on a fairly large data set from a period of active tree growth (July) and was developed within the constraints of prior knowledge (data from D. M. Cole and Jensen 1980).

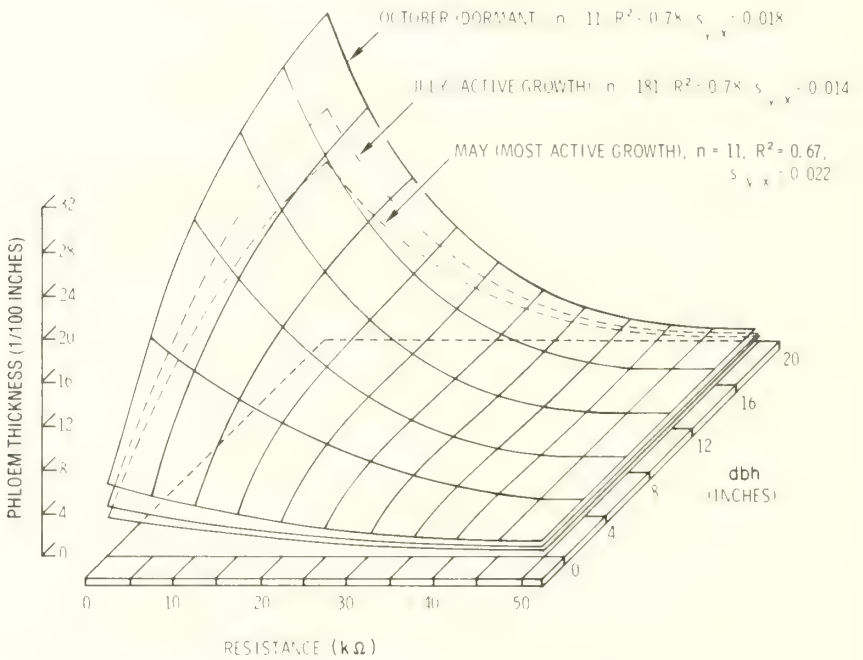


Figure 90.—Phloem thickness of lodgepole pine in relation to d.b.h. and electrical resistance of cambium, the mathematical hypothesis.

Data for May and October were subsequently obtained and appeared to be fairly well represented by the July surface. When the hypothesis was fitted to each of the new data sets independently, the resulting surfaces bracketed that for July as expected. The hypothesis was subsequently tested with new, small data sets.

Explanations of descriptor development that follow, assume familiarity with 2-D descriptor methods discussed earlier.

The July data were sorted into d.b.h.-groups. Within each d.b.h.-group, smoothed trends over R were estimated in accord with expectation (shown schematically in figure 91).

The negative relation of P to R was strongly displayed in the data, so this was the starting point for the descriptor using the reversed R-scale on an estimated intercept of 0.01. Then

$$P = 0.01 + (YP/(45)^n)(50 - R)^n.$$

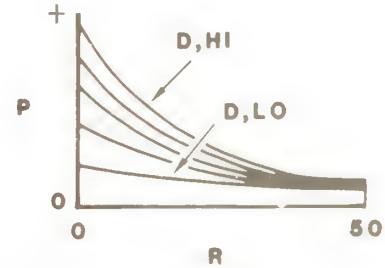


Figure 91.—The schematic trends.

Screening the resulting curves for n in the X^n-Standards, n varied sigmoidally from 1.9 at smaller diameters to about 3.2 at larger ones. The trend was estimated to be as shown in figure 92 where,

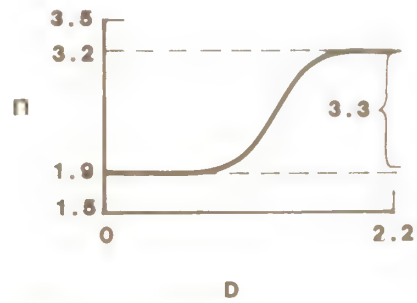


Figure 92.—n smoothed.

$$n = 1.9 + (1.3)e^{\left|\frac{D}{22} - 1\right|^{0.7}}$$

The R-effect was scaled at $R = 5$ or $(50 - R) = 45$, since this was the lower limit of the data over R. The height of the July surface at this point minus the intercept of $0.01 = YP$. YP varied positively (convex upward) with D as shown on the July surface (fig. 90) at $R = 5$. This effect (fig. 93) was described as a double component X^n-function of the re-

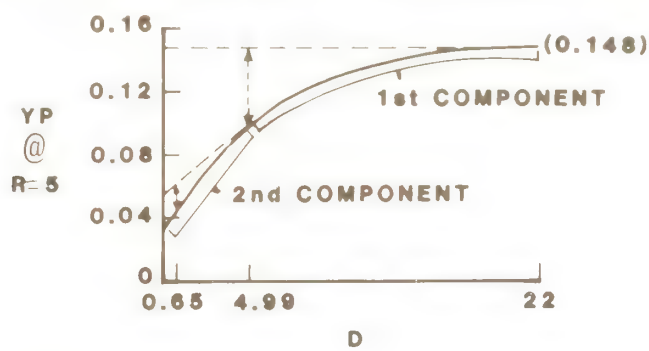


Figure 93.—YP smoothed.

versed D-scale, subtracted from the uppermost YP, $(YP = 0.158 - 0.010 = 0.148)$. The first component was scaled at $D = 4.99$, the second at 0.65. And

$$YP = 0.148 - (2.2687 \times 10^{-5})(22 - D)^{2.72} - (1.2694 \times 10^{-14})(22 - D)^{9},$$

thus completing the inputs for the hypothesis pictured in figure 90. Limits of application are: $0 \leq D22$; $0 \leq R \leq 50$. For $D > 22$, $n = 3.2$ and for $R > 50$, $P = 0.01$.

Based on performance of the hypothesis for the May and October data sets, $R^2 = 0.67$ and 0.78, $s_{y.x} = 0.22$ and 0.018, respectively, the July hypothesis appears to represent other months within reason.

MATHEMATICAL DESCRIPTION OF GRAPHED HYPOTHESES - FIVE DIMENSIONS

Outline for "FIVE DIMENSIONS"

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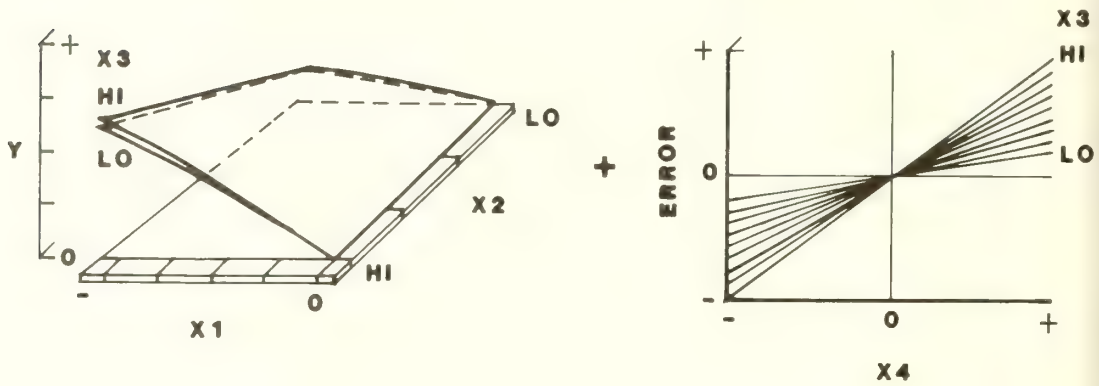
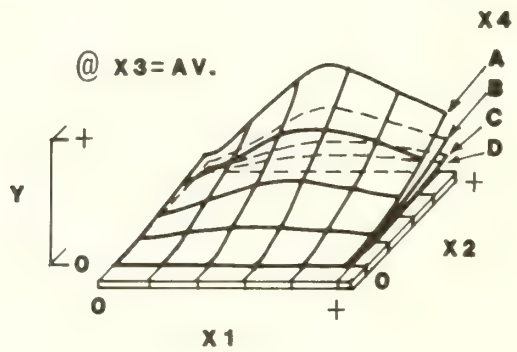
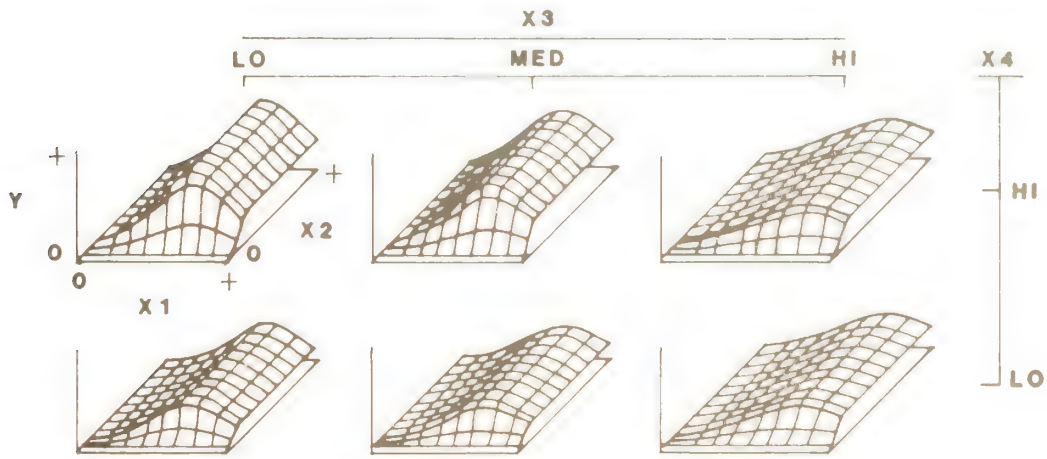


Discrete-Variable Extension of the 4-D Terpene Example 96

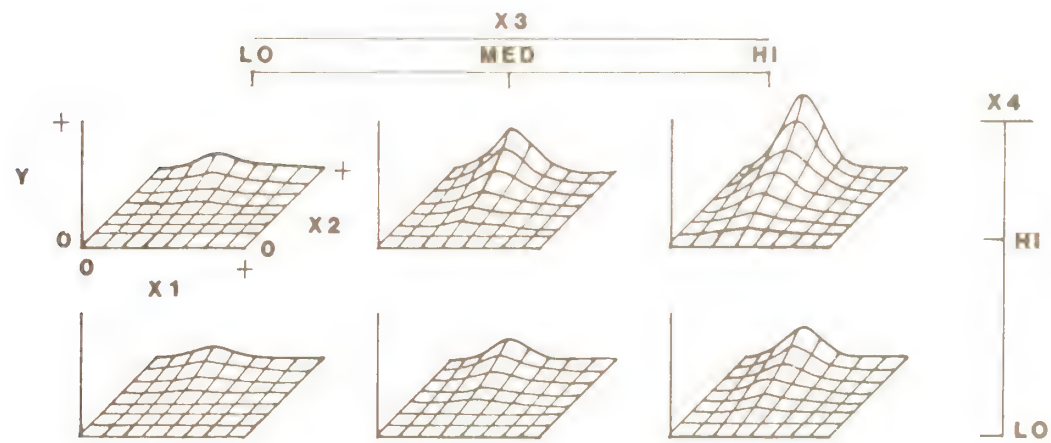


PAGE

Symmetrical Bell-Shaped *X*1-Effect with Moving Peak in *X*3; *X*2, a Sigmoid, Interacts with *X*1 to Form the Ridge Shown, Which Changes in Height Sigmoidally Over the Ranges of *X*3 and *X*4 (Live Data Example) 97



Symmetrical Bell-Shaped *X*1-Effect with Constant Point of Peaking in *X*2. The Interacting Effect of *X*2 is Concave-Upward and Those of *X*3 and *X*4 are Sigmoidal (Live Data Example) 101



Extension of the 4-D Psychrometer Example (Pages 86–89) to Include the Linear Interactive Effects of *X*3 and *X*4

Live Data Example

The Brown and Bartos (1981) four-dimensional thermocouple example (fig. 89 and 94), ultimately had a fifth dimension. It consisted of the variable, zero-offset microvolts

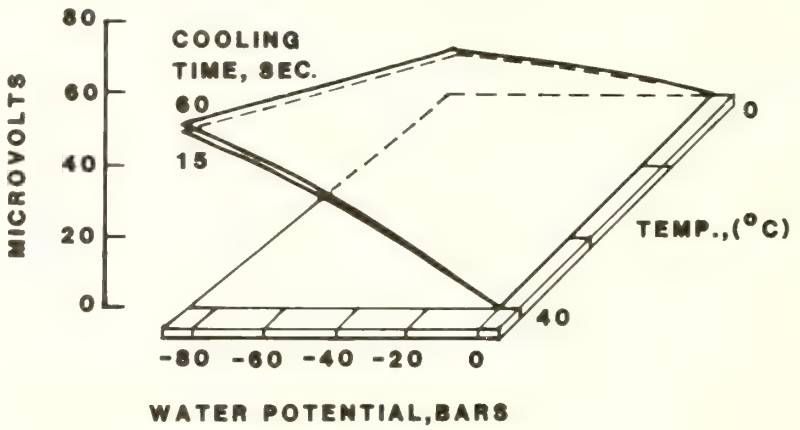


Figure 94.—The 4-D microvolt mathematical hypothesis.

(*ZOM*), and is an index of the temperature differential between the thermocouple sensor tips. Such differential has an effect, zero-offset error (*ZOE*), on the microvolt output that changes depending on the average temperature level of the measured medium and on the direction of the temperature difference between the tips, as indicated in figure 95.

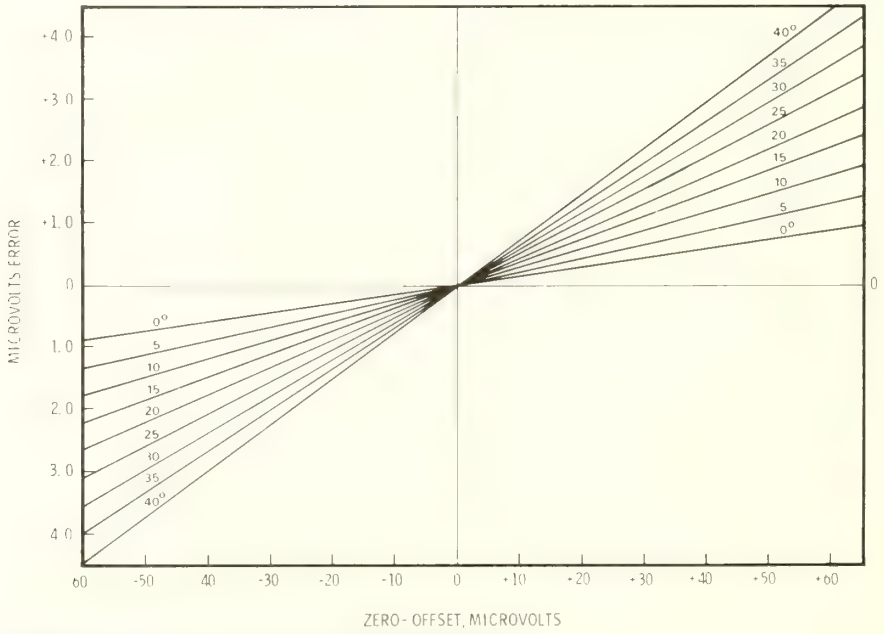


Figure 95.—Zero-offset error source information.

ZOE is quantified in figure 95 only at $CT = 15$ seconds and $WP = -22.5$. A proportional ratio of change, C, for microvolts estimated in the four-dimensional model ($MV4$) is derived from MV-readings at $WP = -22.5$, as specified below:

$$C = \frac{MV_{\cdot} + (MV_{\cdot} - MV_{1<})ZOE}{MV_{\cdot}},$$

where

$MV_{\cdot}$ = MV at specified average temperature, ZOM, and $15 \leq CT \leq 60$

$MV_{1<}$ = as above, but with $CT = 15$.

Then,

$MV5 = MV4(C)$

where

$MV4 = f(CT, T, WP)$, as previously specified, and

$ZOE = b_1(ZOM) + b_2(ZOM)(T)$

where

b_1 and b_2 are estimable directly from figure 96, an annotated version of the right side of the three-dimensional form implied in figure 95.

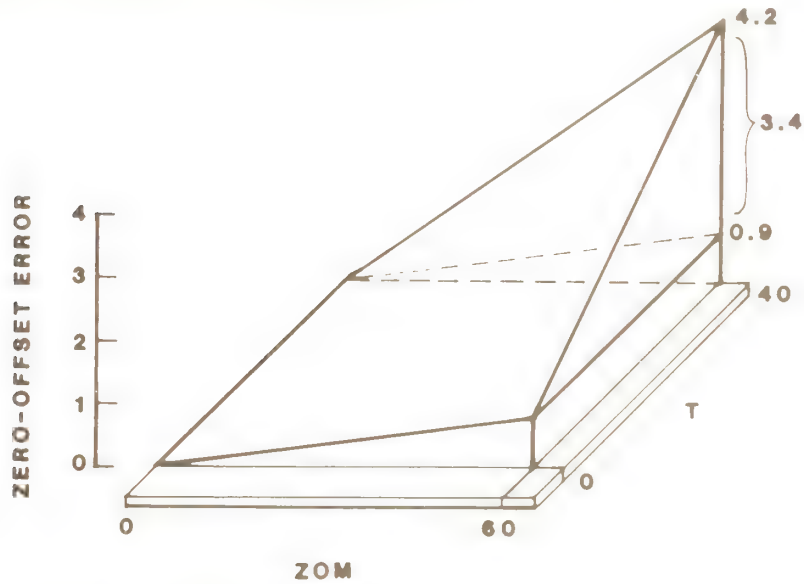


Figure 96.—Zero-offset error in 3-D.

From figure 96,

$b_1 = (0.9/60)(ZOM) = 0.015(ZOM)$

$b_2 = (3.4/60 \times 40))(ZOM)(T) = 0.001471(ZOM)(T)$.

Note that the formula for the right side of figure 95 applies to the left side also, since the sign of ZOM and C both become negative there.

This completes the five-dimensional relation, where $MV5 = MV4(C)$ and

$$MV5 = (UI1 - (UI1/|XP|^{n1})|XP - WP|^{n1})C.$$

Again, with interest focused on WP and solving $MV5$ for WP, we have

$$WP = \left\{ \left\{ \frac{|XP|^{n1}(UI1 \times C - MV)}{UI1 \times C} \right\}^{1/n1} + XP \right\} *(-1), \quad XP \leq WP \leq 0.$$

Discrete-Variable Extension of the 4-D Terpene Model

Live Data Example

Given the 4-D relation already established for total terpenes (fig. 82 and 97), the residual problem of estimating such a relation for each of three component or component groups of the total (beta-phelandrene, beta-pinene + 3-carene + myrcene, and alpha-pinene) was approached. The associated data were screened graphically over D, P, and G, and were found to contain more relative variability than existed with analysis of total terpenes. There did not appear to be, however, any recognizable departure of basic forms from those estimated to exist for total terpenes.

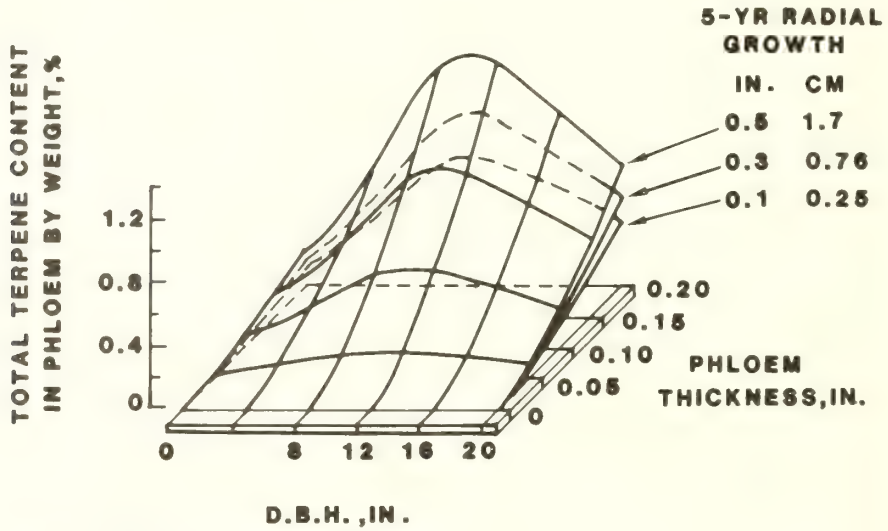


Figure 97.—The 4-D mathematical hypothesis.

Then, the obvious alternative of fitting the relation developed for total terpenes to that for each component or component group by least squares was adopted. That is, where estimated total terpene (T) = X and measured component terpene = Y, the least squares coefficient, b, was

$$b = \Sigma XY / \Sigma X^2.$$

The expected sum of the three coefficients independently obtained was the b of 1.10301 determined for total terpenes (from the 4-D terpene example). So, the three b values were adjusted by the simple ratio of

$$\left\{ \frac{b \text{ for total terpenes}}{\Sigma b_i \text{ for components}} \right\}.$$

Final component coefficients (and associated R^2's) are shown in table 29. Holding G at its average, 1.59, the resulting surfaces appear as in figure 98.

These surfaces would vary jointly as a rather flat concave-upward curve over G since, from the 4-D terpene example,

$$YPD = 0.38 + 1.0292(G)^{1.4}.$$

Table 29.—4-D coefficients and R^2's for terpene components

	b	R^2
Beta-phelandrene	0.64292	0.402
Beta-pinene + 3-carene + myrcene	.30222	.352
Alpha-pinene	.15787	.213
Total terpenes (sum)	1.10301	0.387

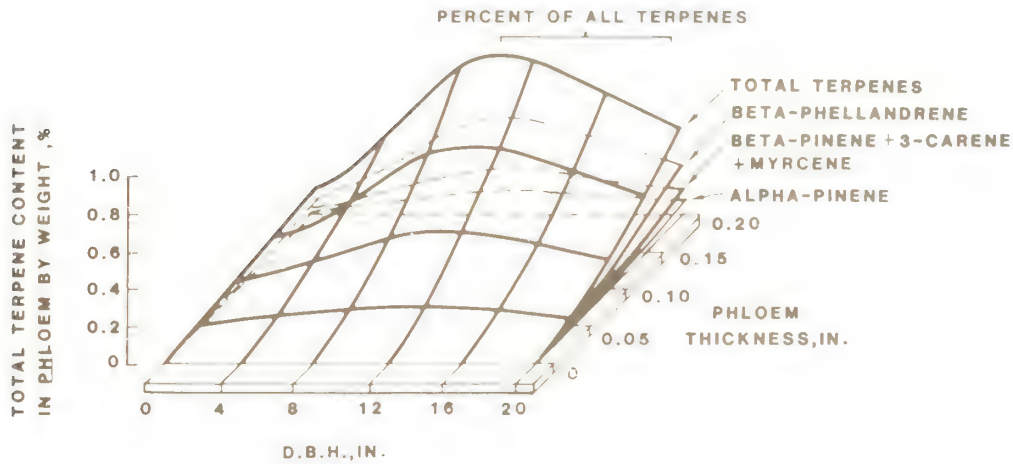


Figure 98.—Discrete partitions for the 4-D terpene hypothesis

Also, since the form of the relation is identical for each component terpene and the total and since component scales sum to that for the total, components will always sum to the total at any point in the relation.

Symmetrical Bell-Shaped $X1$-Effect with Moving Peak in $X3$; $X2$, a Sigmoid, Interacts with $X1$ to Form the Ridge Shown, Which Changes in Height Sigmoidally Over the Ranges of $X3$ and $X4$

Live Data Example

Our hypothesis development here, involves a small data set (from Lee and others 1973) associated with the gap-graded road materials problem discussed under 3-D, asymmetrical bell-shaped ridges. These data were exhausted of information graphically under constraints of expectation to arrive at the mathematical hypothesis shown in figure 99.

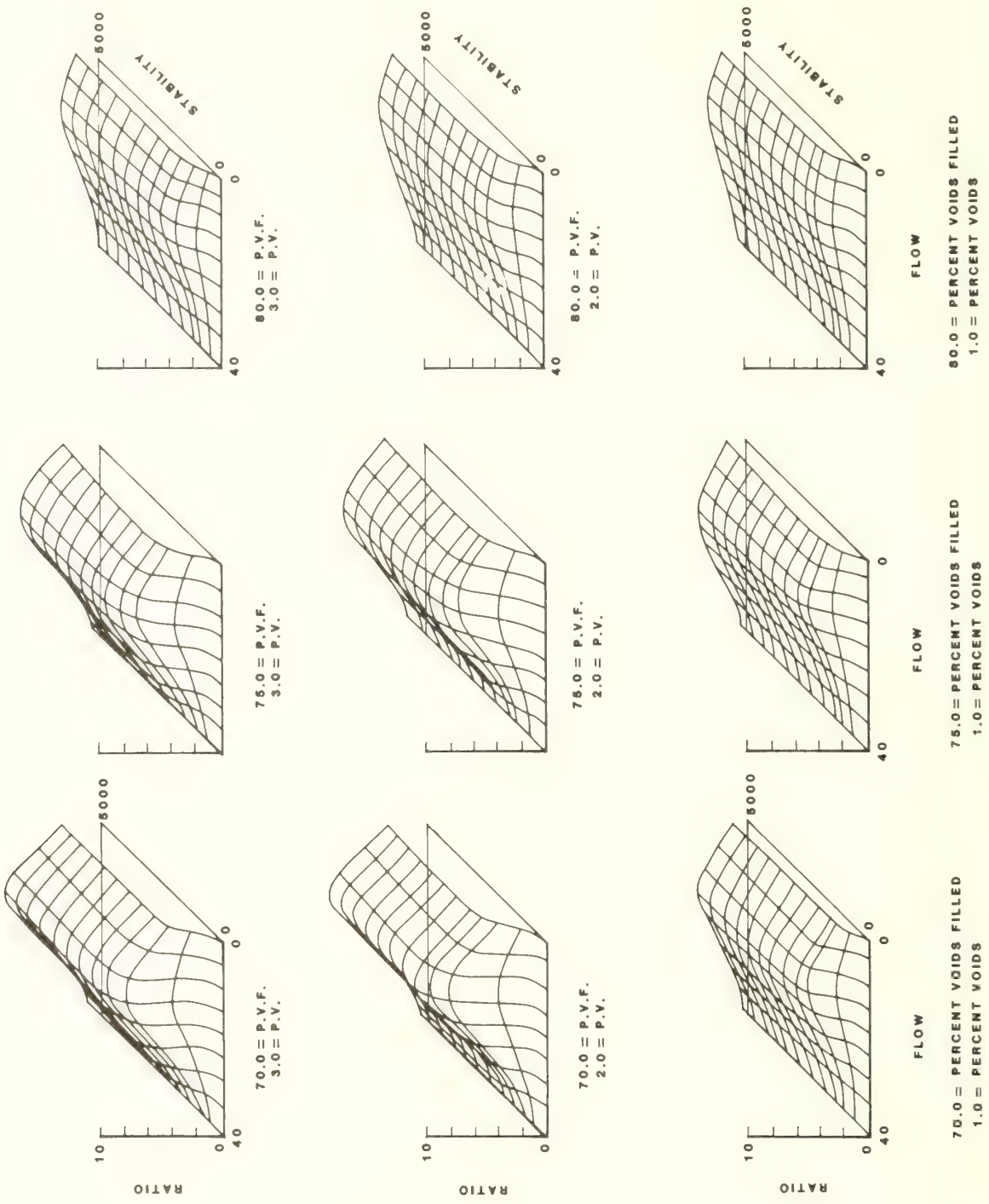


Figure 99.—The mathematical hypothesis.

The explanations of descriptor development that follow presume familiarity with the methods presented in the TWO DIMENSIONS section.

The effect of stability (S) on the dependent variable, ratio (R), was strongly expressed in the data and so was the first effect specified in the descriptor. S appeared to have a consistent sigmoidal shape within partitioned data groupings (some missing because of the small data set) of the remaining three independent variables, flow (F),

percent voids (V), and percent voids filled (VF). This is shown schematically in the top two graphs in figure 100. The starting point in the descriptor is

$$\text{RATE} = (YP)e^{-\left(\frac{S - 1}{500 - 0.9}\right)^{3}},$$

a sigmoid upward to the right over S with zero intercept whose vertical scale, YP, is dependent on the remaining three variables.

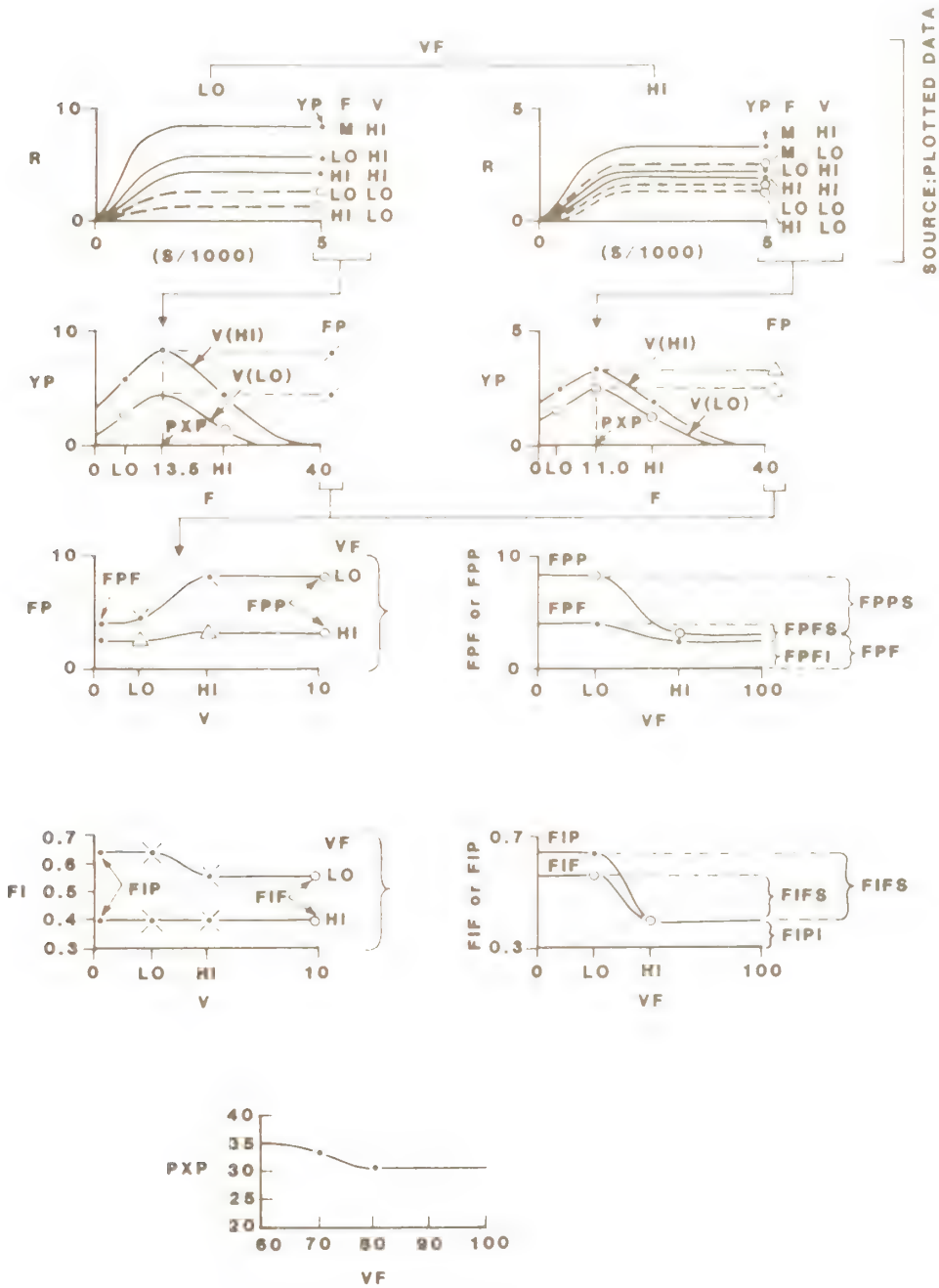


Figure 100.—Sequential development of forms and scalars.

The scalar effect of F at $S=5000$ is bell shaped and symmetrical as may be seen in the two graphs (second pair from the top) in figure 100. Adding 20 to F to accommodate the broadest curve of the set under the constraint that e^{-K} functions only between zero and $2XP$, these curves are described by

$$YP=FP\left\{\frac{e^{-\left|\frac{(F+20)}{\frac{PXP}{1-FI}}-1\right|^{1.6}}-e^{-\left\{\frac{1}{1-FI}\right\}^{1.6}}}{1-e^{-\left\{\frac{1}{1-FI}\right\}^{1.6}}}\right\}$$

where

FP, the scalar for YP, is estimated (conservatively) to vary sigmoidally with both V and VF, as shown in the third tier of graphs from the top of figure 100. The descriptor is

$$FP=FPF+(FPP)e^{-\left|\frac{\frac{V}{10}-1}{0.78}\right|^{50}}$$

and

$$FPF=2.4+(1.8)e^{-\left|\frac{\frac{(100-VF)}{40}-1}{0.42}\right|^{9}}$$

$$FPP=0.8+(2.9)e^{-\left|\frac{\frac{(100-VF)}{40}-1}{0.42}\right|^{9}}$$

where FPP adds $(3.2-2.4=)0.8$ at $VF=100$, and $(7.9-(2.4+1.8+0.8)=)2.9$ at $VF=0$. PXP is mobile and is assumed to be sigmoidal as shown in the graph at the bottom of figure 100. PXP changes with VF only and can be identified as

$$PXP=31+(2.8)e^{-\left|\frac{\frac{(100-VF)}{40}-1}{0.42}\right|^{9}}.$$

And the inflection points (FI) for the bell-shaped YP-curves vary with V, as shown in the left graph of the two just above the one for PXP. The graph to the right of that shows associated sigmoidal trends (assumed) over VF for intercepts (FIF) and peaks (FIP). All told, the descriptor for FI is as follows

$$FI=FIF+(FIP)e^{-\left|\frac{\frac{(10-V)}{10}-1}{0.27}\right|^{10}}$$

where

$$FIF = 0.41 + (0.15)e^{-\left(\frac{(100-VF)}{40}-1\right)^{2}/0.42}$$

$$FIP = (0.08)e^{-\left(\frac{(100-VF)}{40}-1\right)^{2}/0.42}$$

This chain of descriptor components is converted to the Fortran IV statements shown below:

```
T = (EXP( - (ABS(((100 - VF)/40) - 1)/.42)**9)))
PXP = 31 + 2.8*T
FPF = 2.4 + 1.8*T
FPP = .8 + 2.9*T
FIF = .41 + .15*T
FIP = .08*T
FP = FPF + FPP*(EXP( - (ABS((V/10 - 1)/.78)**50)))
FI = FIF + FIP*(EXP( - (ABS(((10 - V)/10 - 1)/.27)**10)))
LN = EXP( - (ABS(((F + 20)/PXP - 1)/(1 - FI))**1.6))
RN = EXP( - ((1/(1 - FI))**1.6))
YP = FP*((LN - RN)/(1 - RN))
RATE = 1.0315*YP*(EXP( - (ABS((S/5000 - 1)/.9)**35)))
```

Note that the coefficient of 1.0315 resulted from the refitting of the mathematical model back through the data from which it was derived by least squares. Given that modeled rates = X and actual rates = Y, $b = \Sigma XY/\Sigma X^2$. Then bX (or $RATE$) is the model submitted to electronic computer/plotter processing that resulted in the graphic presentation of the mathematical hypothesis in figure 99.

It is of interest that the additive model with linear effects of S, F, V, and VF, reached an R^2 of only 0.42 under least squares fit, while, for the model just derived, $R^2 = 0.80$. There would appear to be substantial benefit from utilizing all information at hand for developing the hypothesis in this case.

Symmetrical Bell-Shaped $X1$-Effect with Constant Point of Peaking in $X2$. The Interacting Effect of $X2$ is Concave-Upward and Those of $X3$ and $X4$ are Sigmoidal

Live Data Example

The flexibility of e^{-K} in representing a complex relation is again evident in the five-dimensional interaction pictured in figure 101.

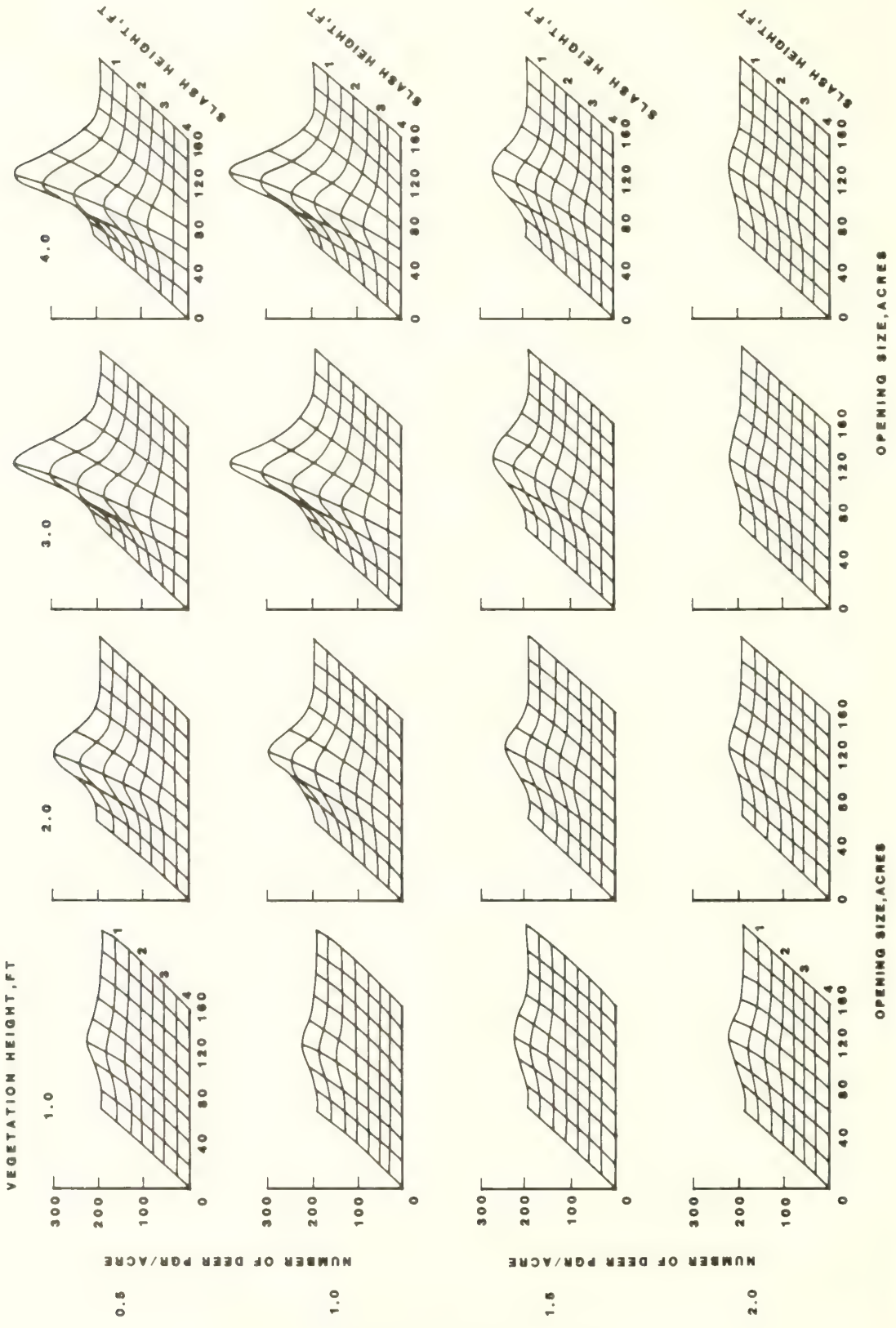


Figure 101.—Deer pellet groups as five-dimensional function of clearcut opening characteristics.

Here, data from Lyon 1976 and Lyon and Jensen 1980 were the basis for an index to intensity of deer use of forest openings created by clearcutting in western Montana. The index is expressed as a function of opening size, height of new vegetation, depth of slash in the opening, and depth of dead and down timber adjacent to the opening.

The data at hand were initially committed to statistical evaluation of the linear effects of the above variables and other independent variables on the intensity index. These were virtually the simplest regression hypotheses that could have been adopted. In this case, the evaluation provided only weak support for expected results and yielded little new information.

To exploit the data further, a hypothesis was developed for the set of four independent variables above. Prior knowledge of the forms of the relations, including interactions, between these variables was summarized. Subject to these constraints, the limited data were then partitioned and graphically exhausted of associated curve-form and scaling information. Data appeared to provide strong support for the dynamic interaction anticipated. Procedures specified here were used to develop a functional form, XT, for the graphed interaction. This was refitted to the data by least squares in the model $PGR = b(XT)$ and $b = 0.9721$. The adjusted model is specified below:

$$PGR = f(VI, SI, SO, \text{Acres})$$

where,

PGR = number of deer pellet groups per acre inside the opening.
VI = height of vegetation in feet, inside the opening.
SI = depth of logging slash in feet, inside the opening.
SO = depth of dead and down timber, in feet, outside the opening.
Acres = size of opening in acres.

If $SI < PO$

$$PGR \quad \left\{ \frac{YP}{(PO - 0.6)^{1.55}} \{PO - SI\}^{1.55} \right\} (0.9721)(50)$$

where

$$YP = YPS \left\{ \frac{e^{-\left| \frac{\frac{\text{Acres} + 200}{260}}{1 - I} \right|^{1.5}} - e^{-\left| \frac{I}{1 - I} \right|^{1.5}}}{1 - e^{-\left| \frac{1}{1 - I} \right|^{1.5}}} \right\} + 0.23$$

$$YPS = 0.57 + 3.23 \left\{ e^{-\left| \frac{VI - 1}{0.76} \right|^{20}} \right\} \left\{ e^{-\left| \frac{3 - SO - 1}{0.4942} \right|^{10}} \right\}$$

$$PO - 6.289 e^{-\left| \frac{VI - 1}{0.999} \right|^{10.5}} 2.289$$

$$I = 0.897 - 0.067e^{-\left|\frac{\frac{VI}{8} - 1}{0.404}\right|^{3.5}}.$$

If $SI > PO$

$PGR = 0$

Limits

$0 \leq SI \leq 4,\ 0 \leq SO \leq 3,\ 0 \leq VI \leq 8,\ 0 \leq \text{Acres} \leq 300.$

Graphic development of the model described by this function apparently resulted in great sensitivity to the interaction information contained in the data. But, since the degrees of freedom thereby sacrificed were unknown, conventional statistical parameters were not estimable. Some indication as to the goodness-of-fit of the functional form to the data set from which it was largely derived is provided by the proportion of the total sum of squares explained by the model, $R^2 = 0.71$ here.

Contrast this with the R^2 of 0.21 achieved with a minimum-effort additive regression model where linear effects of the same four independent variables have been fitted to the data by least squares. It would appear that sharp focus on interaction formulation was justified.

At this point in the paper, it is assumed that only a minimum of explanatory information will be necessary to clarify descriptor development.

The expected negative *SI* effect was strongly apparent in the data and so was used as the starting point for the descriptor. This effect was exponential over the reversed *SI*-axis where $0.6 \leq SI \leq PO$. The lower extreme of the data in *SI*, 0.6, was adopted as the scaling point (largest *PGR*-values) in the reversed *SI*-scale. *PO*, a variable over *VI*, represented the point in *SI* where the *PGR*-curves reached zero (fig. 102).

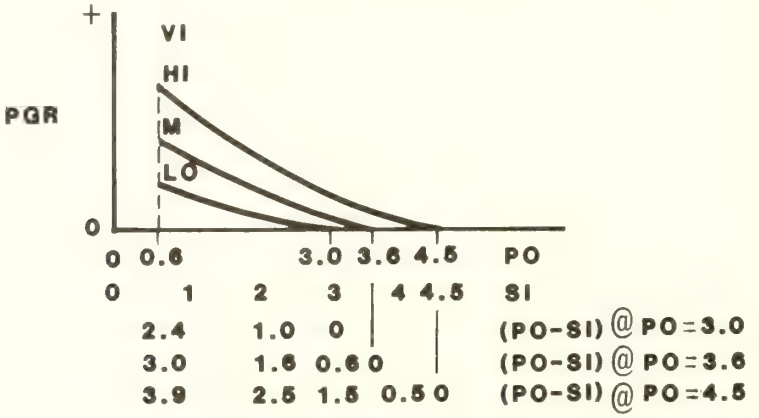


Figure 102.—The *SI*-effect with changing points of origin, *PO*.

When the point of exponential origin was allowed to vary, n in X^n approached a constant (1.55) over *SI*, but the scaling heights of these curves ($@SI = 0.6$) varied over *ACRES*, *VI* and *SO*.

Then,

$$PGR = (50 \times b)(YP/(PO - 0.6)^{1.55})(PO - SI)^{1.55},\ SI \leq PO$$

where

50 is the constant necessary to the conversion of data units to acres;

b is the least squares coefficient fitting the derived model back through the source data.

Note that segmentation is employed in the exponential variable here, since beyond *PO* in *SI, PGR* is specified as zero. *PO* varied sigmoidally over *VI* and

$$PO = 6.289e^{\left(\frac{\left(\frac{VI}{10}-1\right)^{10.5}}{0.999}-2.289\right)}$$

$$YP = 0.23 + YPS\left\{\frac{e^{\left(\frac{\left(\frac{\text{Acres}+200}{260}\right)^{1.75}-1}{1-I}\right)}-e^{\left(\frac{1}{1-I}\right)^{1.75}}}{1-e^{\left(\frac{1}{1-I}\right)^{1.75}}}\right\}.$$

XP appeared constant at 260 acres and, from the $e^{-\lambda}$-Standards, $n = 1.75$ was reasonably representative for all curves. *I*, however, varied sigmoidally over *VI* and

$$I = 0.897 - 0.067e^{\left(\frac{\left(\frac{VI}{8}-1\right)^{2}}{0.404}\right)}.$$

YPS, the heights of the bell-shaped curves over *ACRES*, varied as an interaction of sigmoids, a new descriptor feature. *YPS* varied sigmoidally over *VI* as

$$YPS = 0.57 + 3.23e^{-\left(\frac{\left(\frac{VI}{8}-1\right)^{2}}{0.76}\right)}.$$

but only achieved this magnitude of effect at smaller *SO*-values. The *VI*-effect became sigmoidally smaller as *SO* increased. Noting that the unscaled sigmoid over the reversed *SO*-axis $(3 - SO)$ ranges in value from zero to one, the *SO*-effect,

$$e^{-\left(\frac{\left(\frac{3-SO}{3}\right)^{10}-1}{0.492}\right)},$$

becomes a convenient multiplier with which to achieve the appropriate sigmoidal reduction of the maximum *VI*-effect.

All curve-form estimates were derived from data-based graphic hypotheses, normalized control points, overlay curves, and comparison to either the X^n- or $e^{-\lambda}$-Standards. While

the foregoing mathematical specifications may seem voluminous, they are quite easily specified in a short Fortran IV program for computer processing, as shown:

```
PO=6.289*(EXP(-(ABS((VI/10-1)/.999)**10.5)))-2.289
IF(SI.GT.PO)GO TO 1
A=EXP(-(ABS(((3-SO)/3-1)/.492)**10))
B=EXP(-(ABS((VI/8-1)/.76)**20))
YPS=3.23*A*B+.57
I=.897-.067*(EXP(-(ABS((VI/8-1)/.404)**3.5)))
LN=EXP(-(ABS(((ACR+200)/260-1)/(1-I))**1.75))
RN=EXP(-((1/(1-I))**1.75))
YP=YPS*((LN-RN)/(1-RN))+.23
PGR=(YP/(PO-.6)**1.55)*((PO-SI)**1.55)*(0.9721)*50
X(5)=PGR
RETURN
1 X(5)=0
RETURN
END
```

Note that figure 102 was plotted electronically using a program that incorporated the above statements.

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APPENDIX-A: e^{-K} DERIVATION

e^{-K}: Its Derivation, Potentials, and Limitations

The new function, simply identified as e^{-K}, provides the analyst with a finite source of versatile transformations for use when it is inefficient to search for alternatives or when alternatives are inadequate. While e^{-K} is not a panacea for all the problems modelers face in developing functional relationships, it along with curves of the class $X^n (n \geq 1)$ does serve a broad spectrum of transformation needs with no particular limitations as to curve shapes for which it is most useful. Methods for developing mathematical descriptors using these functions have been treated by Jensen and Homeyer (1970, 1971) and Jensen (1973, 1976, and 1979) and are summarized and updated in this paper.

A variant of the Normal function e^{-K} is defined as:

$$e^{-K} = \left\{ \frac{e^{-\left|\frac{(X/XP)-1}{(1-I)}\right|^n} - e^{-\left\{\frac{1}{(1-I)}\right\}^n}}{1 - e^{-\left\{\frac{1}{(1-I)}\right\}^n}} \right\}, \quad 0 \leq X \leq 2Xp$$

where,

e = natural logarithm base.
XP = pivot point in X for e^{-K} and is the point in X at which the bell-shaped curve peaks.
XI = point of sigmoidal inflection in X.
I = proportional departure of XI from zero to XP or from $2XP$ to XP.
n = power of negative exponents for e.

The left numerator, like the Normal function, generates a system of bell-shaped curves about a central point in X, XP in this case. These curves reach the maximum value of 1.0 at XP and then decline sigmoidally and symmetrically on either side of XP with increasing departure of X from XP.

User control of the curve system is enhanced if all curves of the set range in value from zero to one within a finite domain of X. To achieve this property, curves generated by the left numerator have been forced through zero at $XP \pm XP$ as follows:

Let the left numerator $= e^{-T}$ and let $e^{-T_0} = e^{-T}$ at $X = 0$ or $2XP$. Consider the residuals generated by $1 - e^{-T}$. Expanded by the inverse $(1 - e^{-T_0})^{-1}$ and subtracted from one, we have

$$e^{-K} = 1 - (1 - e^{-T_0})^{-1}(1 - e^{-T}),$$

which simplifies to the final form

$$e^{-K} = (e^{-T} - e^{-T_0})(1 - e^{-T_0})^{-1}.$$

Then the right numerator and the denominator serve to force curves of the left numerator through zero at $XP \pm XP$. This domain, along with XP, can be altered to accommodate the needs of individual conceptual models by adding constants ($+$ or $-$) to the X-scale. The apparent complexity of e^{-K} is much reduced by the fact that in application, the right numerator and the denominator simplify to constants or approach zero and can be deleted.

APPENDIX A (con.)

Sigmoids on either side of XP are forced into different areas of two-dimensional space by shifting I, the proportional point of inflection in X, and the slope of the sigmoidal face at I changes with n.

Arrays of curves from the left half of this function (a mirror image of the right half) are shown in the e^{-K}-Standards that follow. Sets are given for commonly used increments of n, $1.2 \leq n \leq 10.0$. Each set has curves progressing from $I = 0.1$ at the left to 0.9 at the right. These curves or any portions thereof provide an almost endless potential for matching graphed curves and describing them mathematically. Given that YP is the peak value of Y (the dependent variable) on the objective curve, the selected e^{-K} -function (e^{-K} ranges from zero to one) may be scaled to that curve through multiplication by YP.

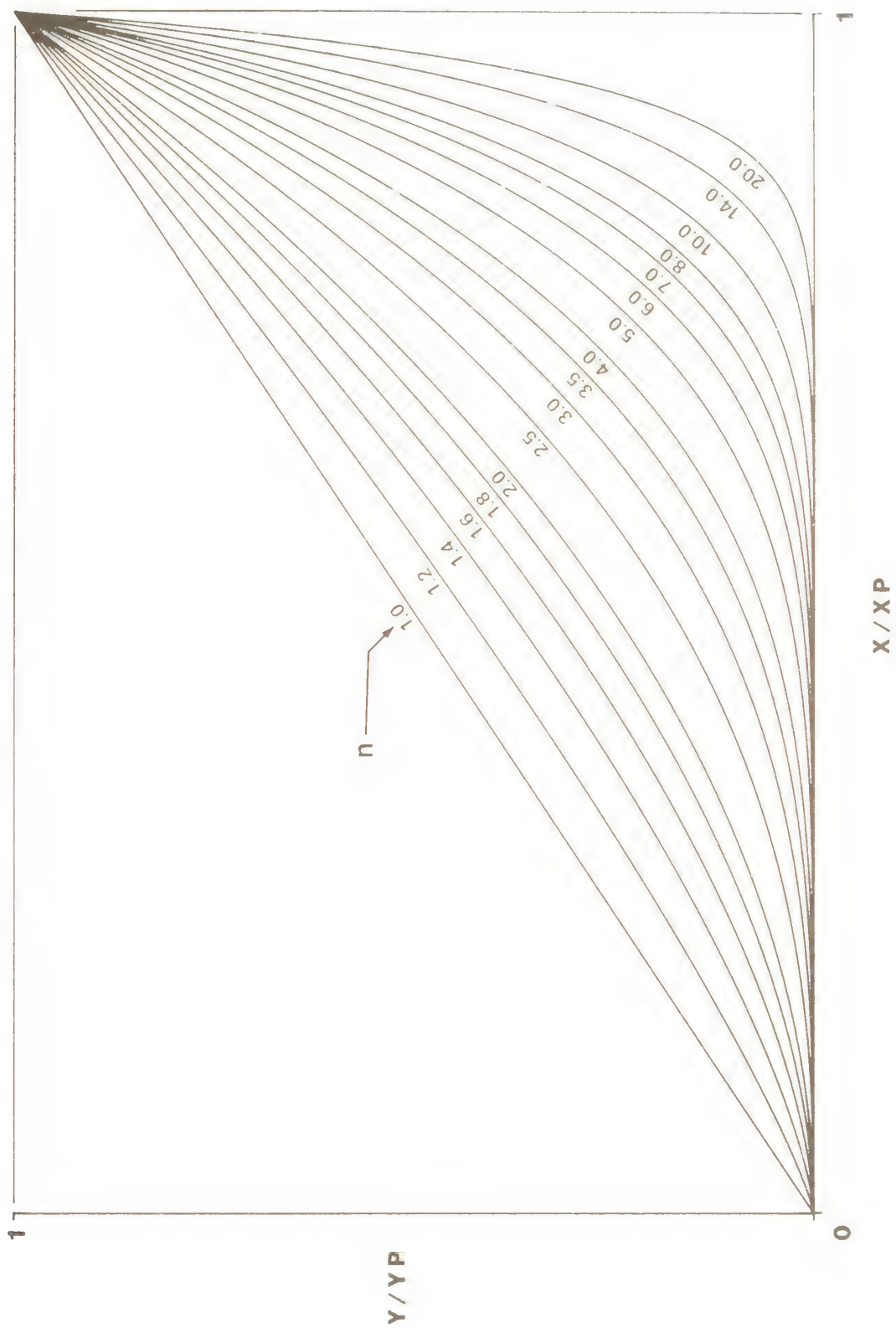
While the controllable parameters I, n, XP, and YP provide exceptional descriptive power in two dimensions, such power is magnified manyfold for hypotheses involving three or more dimensions, as well as strong interactions. For example, the location of peaks Y that move across the independent variables in any fashion can be described with $XP = f_1(X_i)$. The heights of these peaks in any pattern and changing sigmoidal shapes leading up to them can again be pictured as functions of the independent variables $YP = f_2(X_i)$, $n = f_3(X_i)$, and $I = f_4(X_i)$. Additionally, asymmetry in bell-shaped hypotheses is easily accounted for by describing sigmoids on either side of XP independently (segmented descriptors), while scaling both to the same height at XP.

A descriptor (XT), adopted as a hypothesis in its entirety, may be fitted to pertinent data by least squares in the simple model, $Y = \beta XT + \epsilon$. where the ϵ are $NID(0, \sigma^2)$, constant variance, and $\beta = \Sigma XTY / \Sigma XT^2$.

Weighted regression procedures are recommended where the variance about regression is not uniform over the ranges of the independent variables. In such cases, reasonable success in achieving constant variance has been obtained by solving for departures $(Y_i - Y_i)^2$ or d_i^2 as a suitable function of the related Y_i in $d_i^2 = bY_i^n$. Then the weight, w, for each observation is set equal to $1/Y_i^n$ and a weighted β in $Y = \beta Y$ is estimated as $\beta = \Sigma wYY / \Sigma wY^2$.

More complex, generally iterative fitting procedures, such as the Newton–Raphson methods, can be used to arrive at statistical estimates of internal model parameters (see Damaerschalk and Kozak 1977; Draper and Smith 1966).

APPENDIX-B: X^n - STANDARDS



APPENDIX-C: e^{-K} - STANDARDS

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APPENDIX C (con.)

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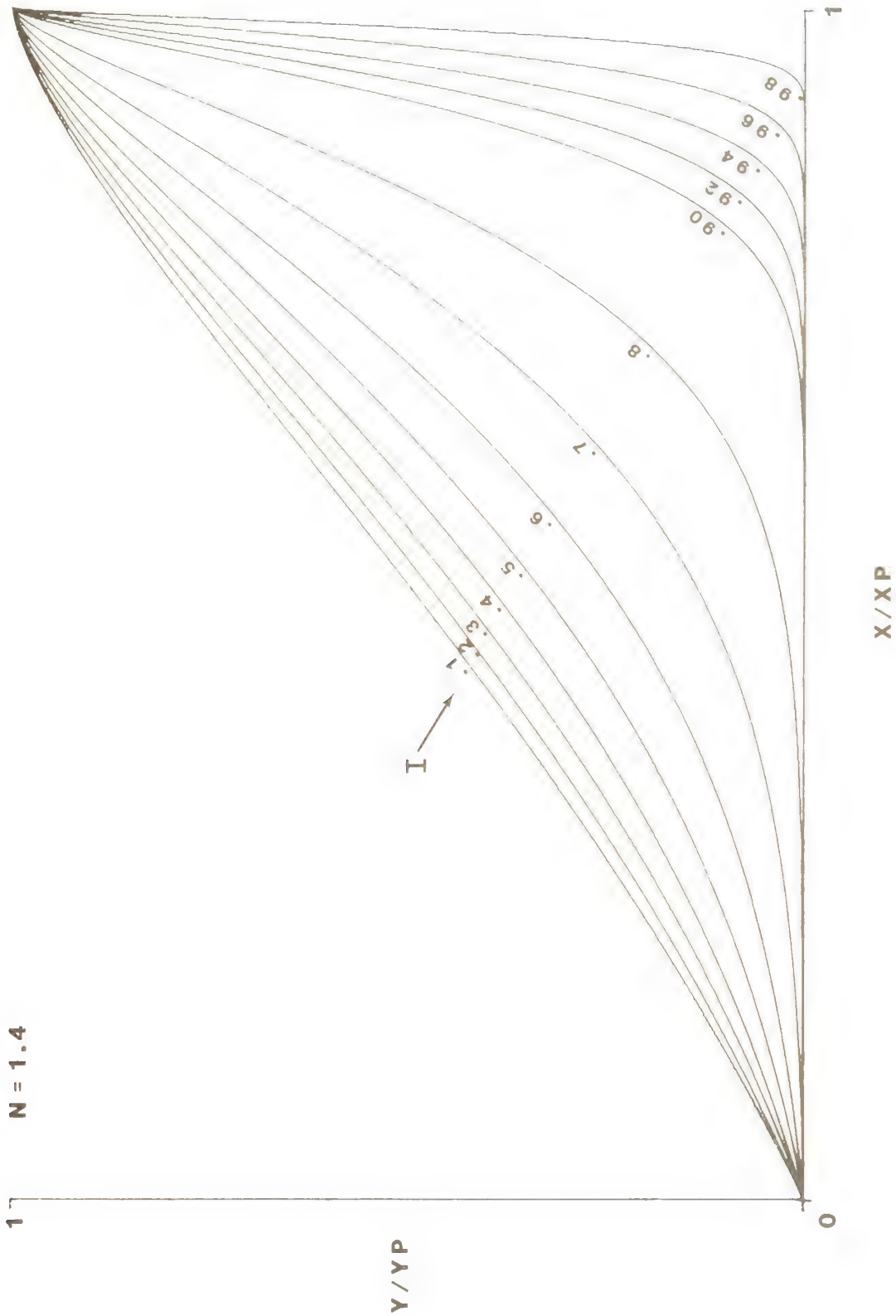
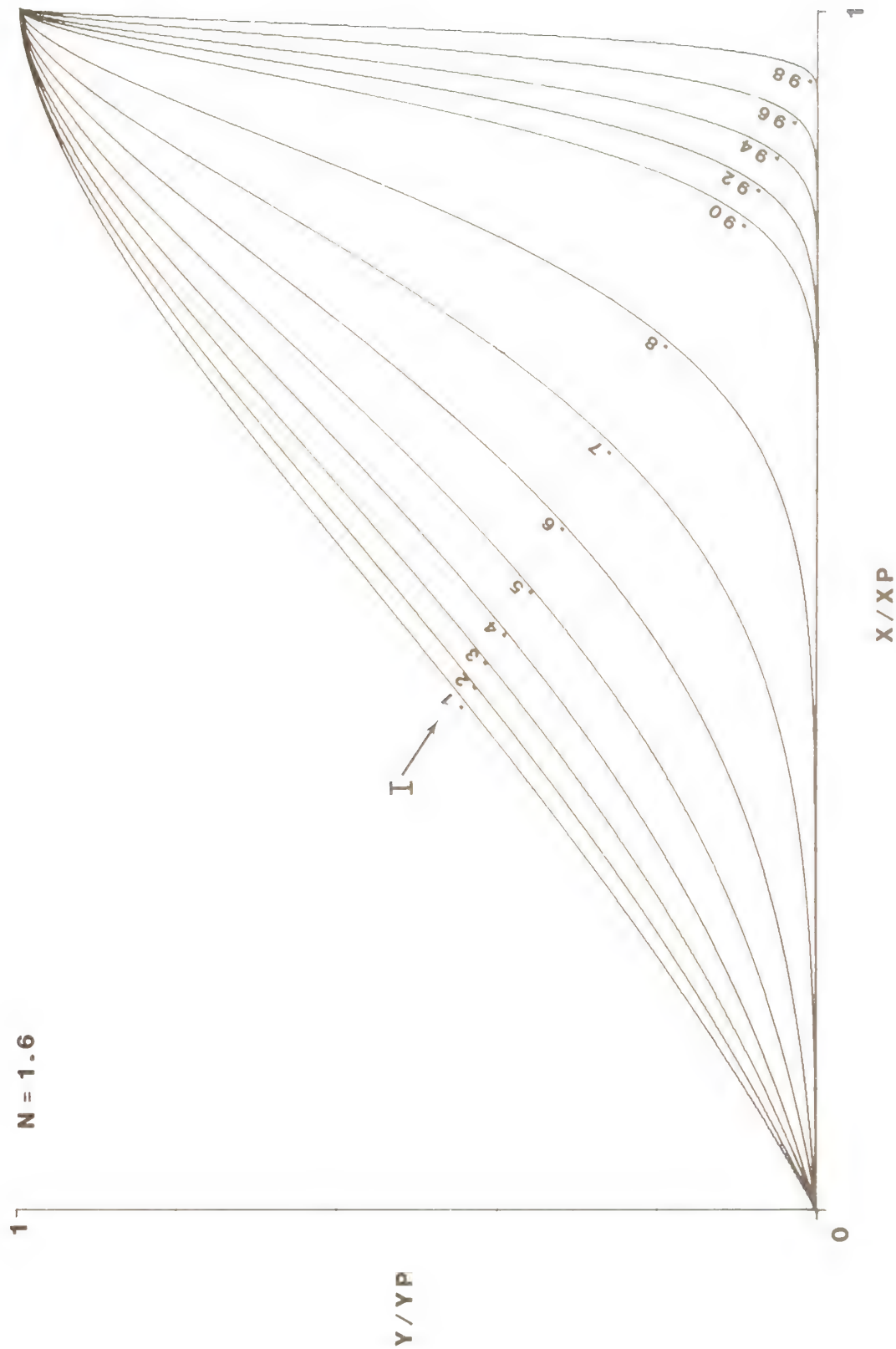


APPENDIX C (con.)



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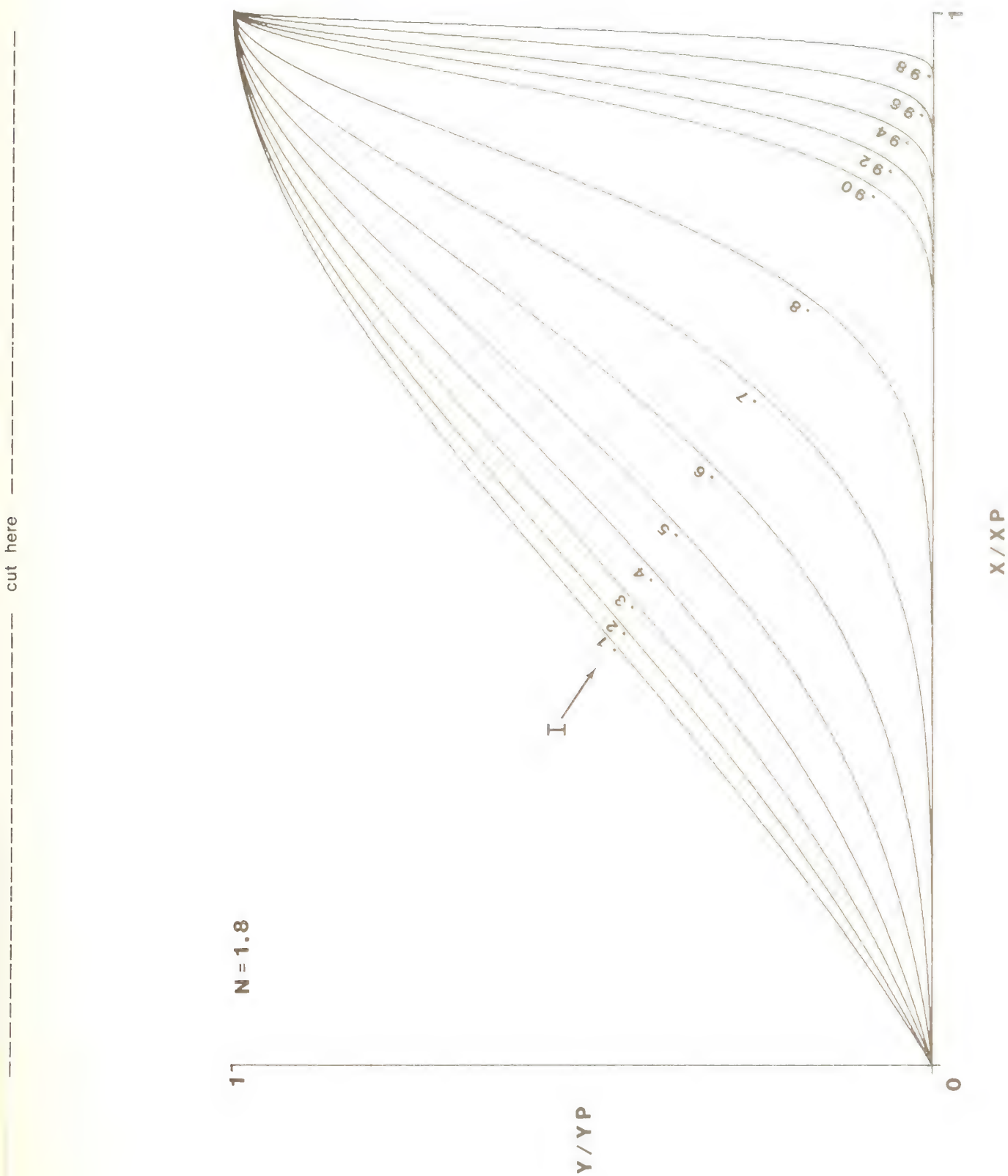
APPENDIX C (con.)



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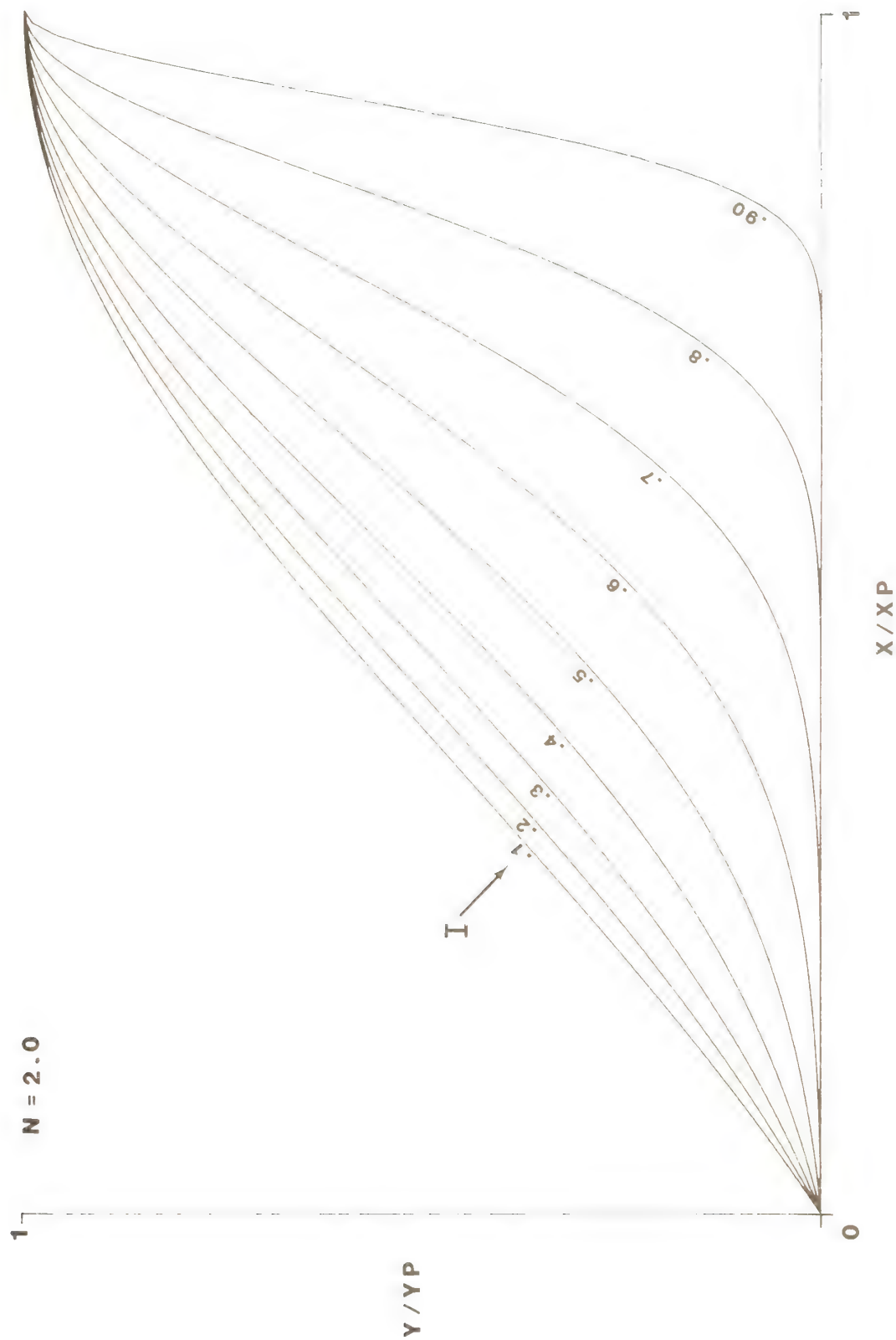
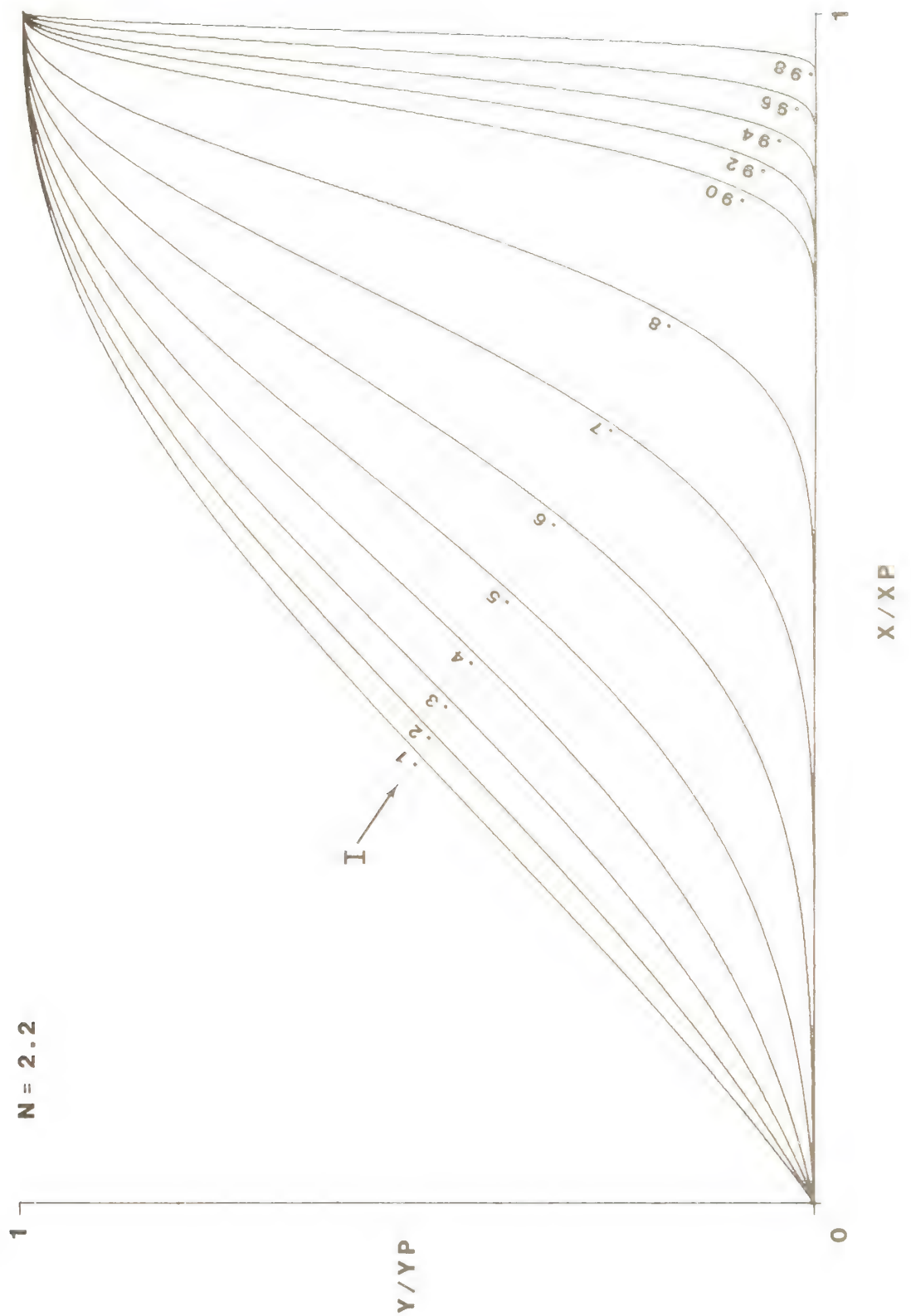
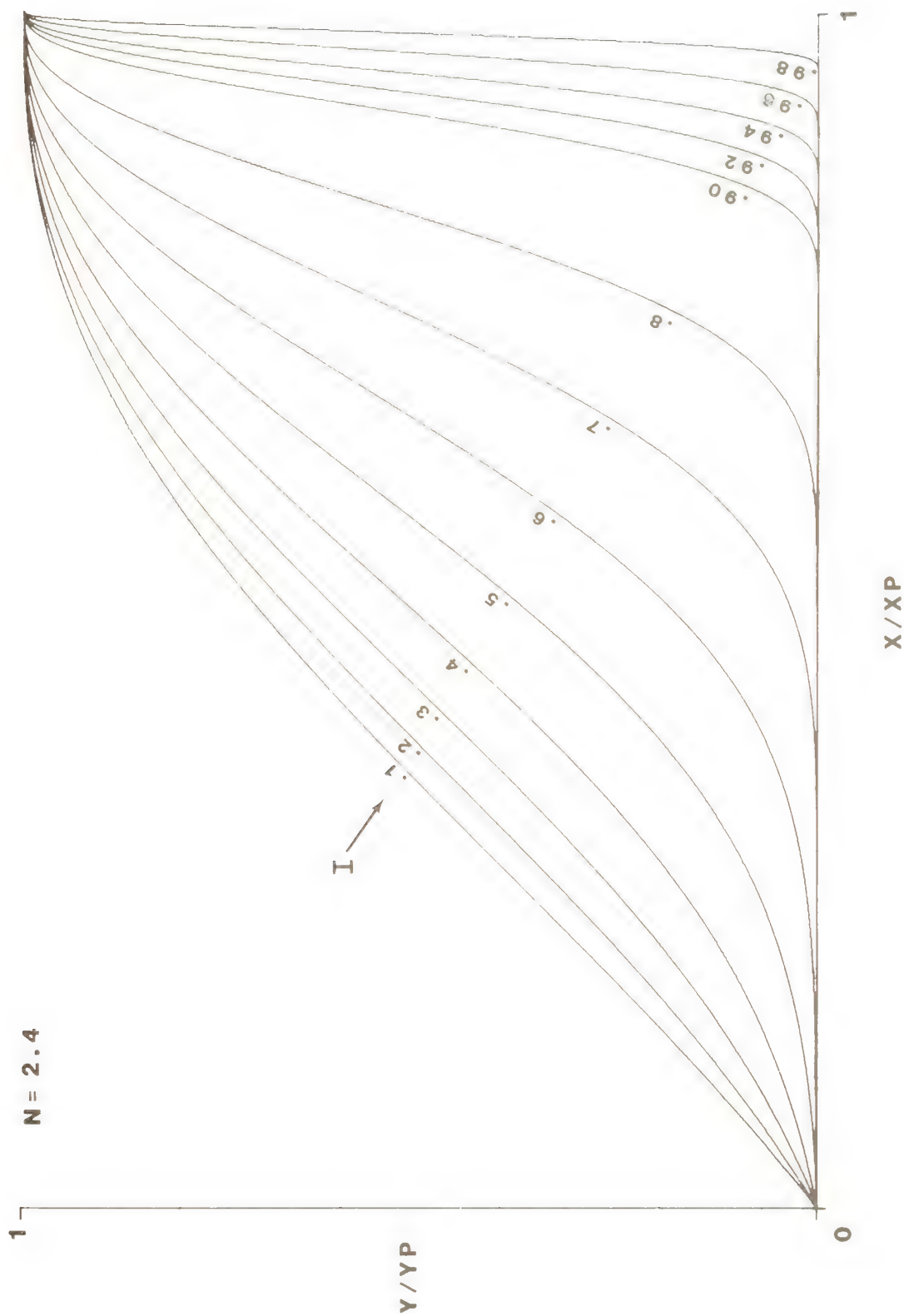


APPENDIX C (con.)



APPENDIX C (con.)



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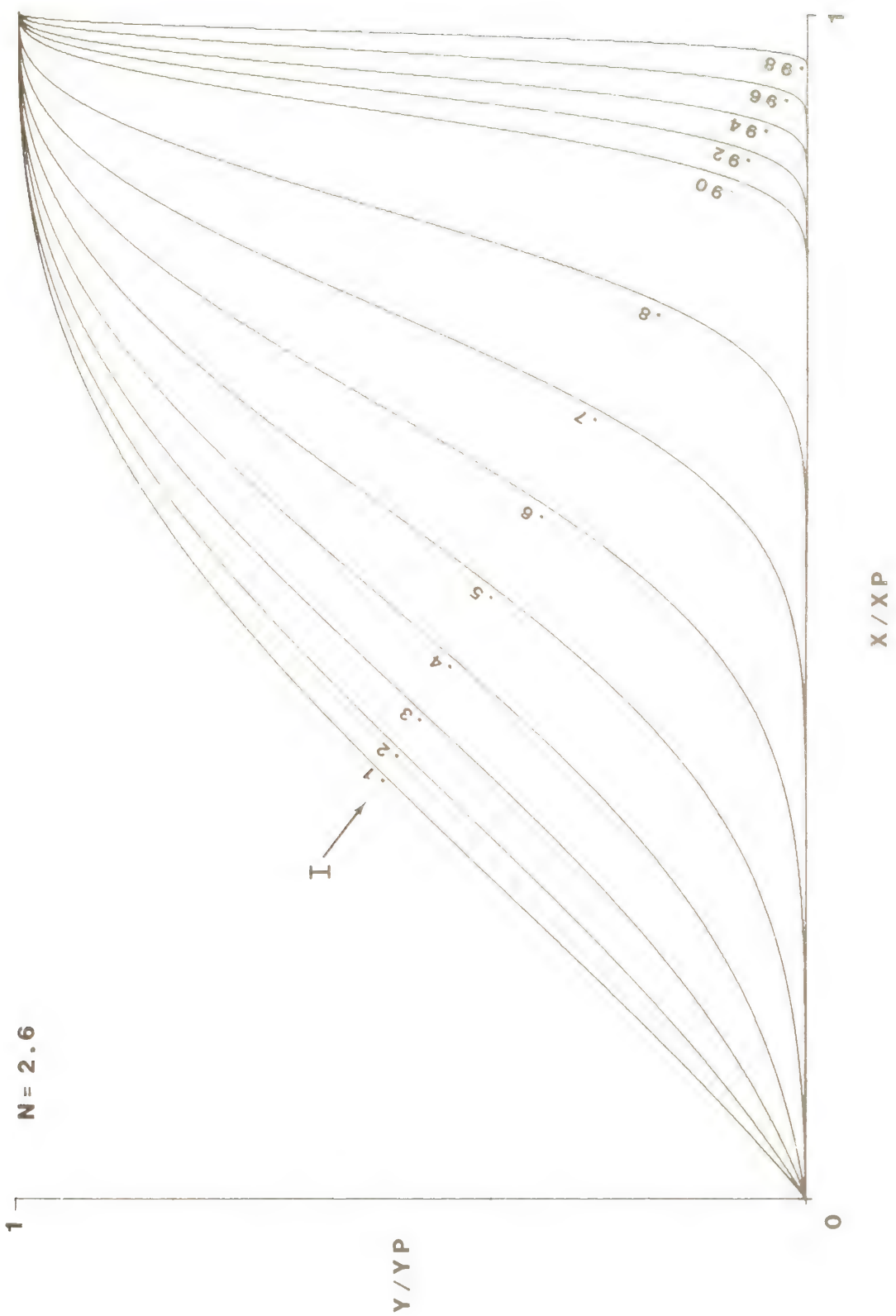

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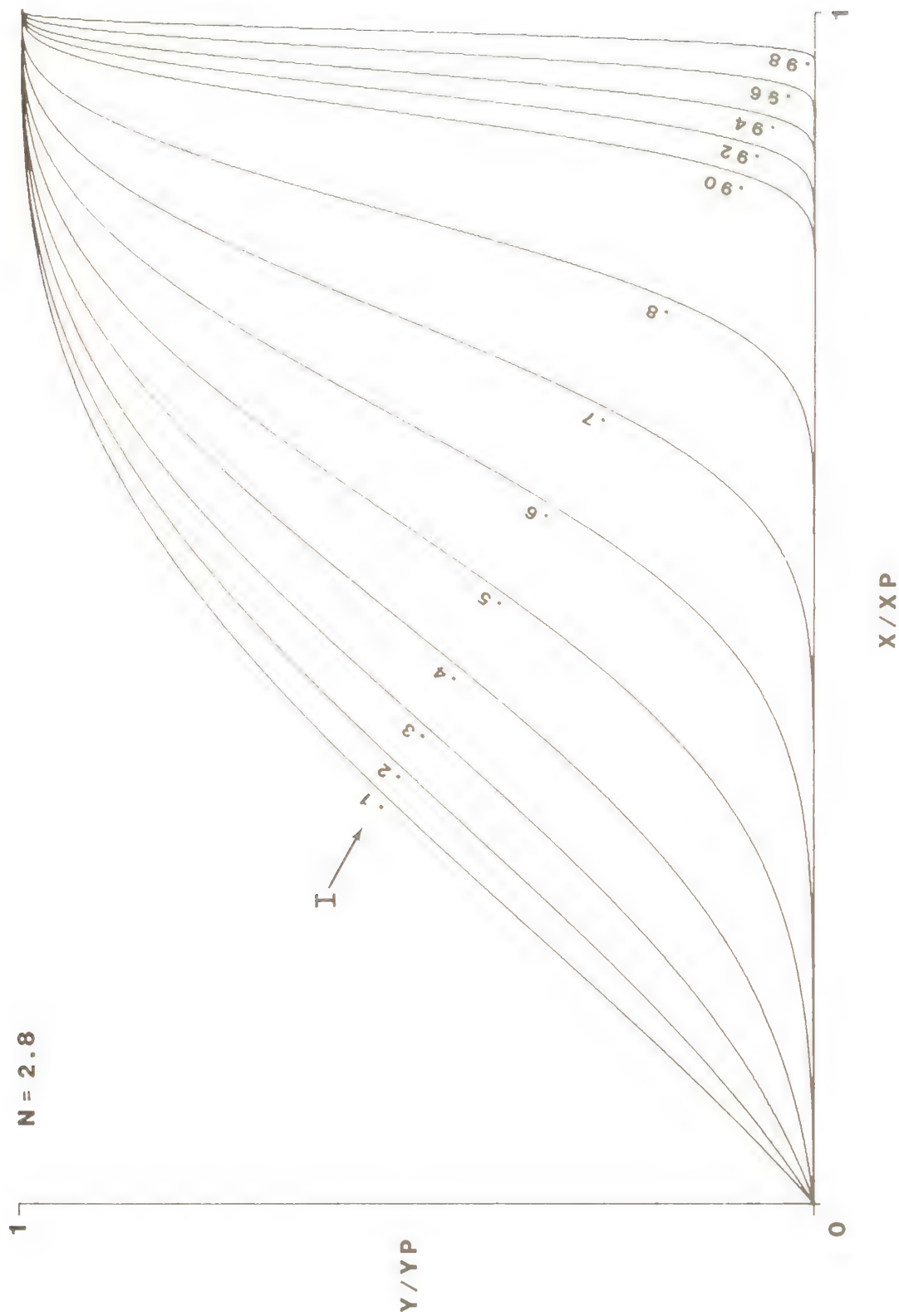

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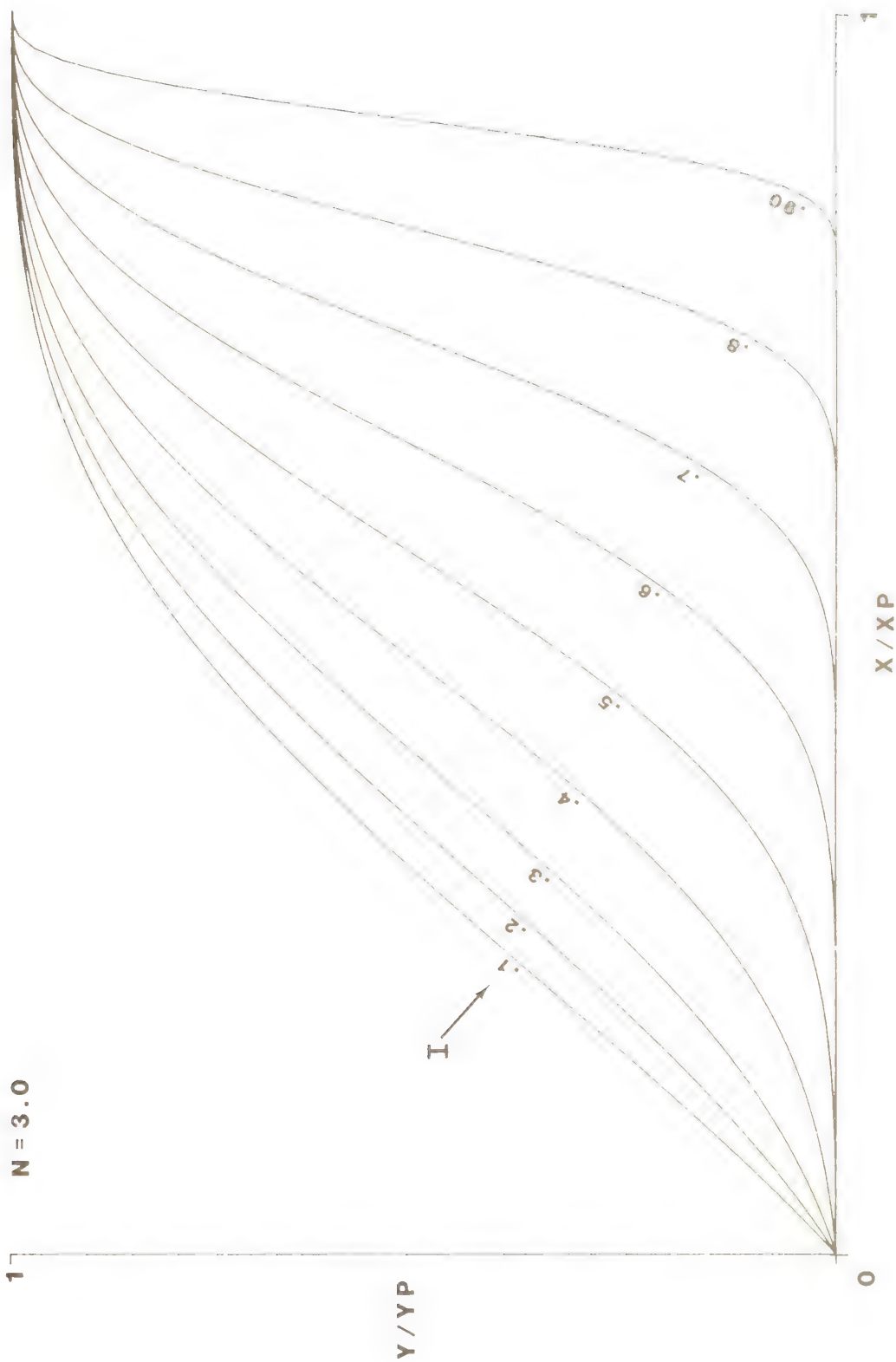

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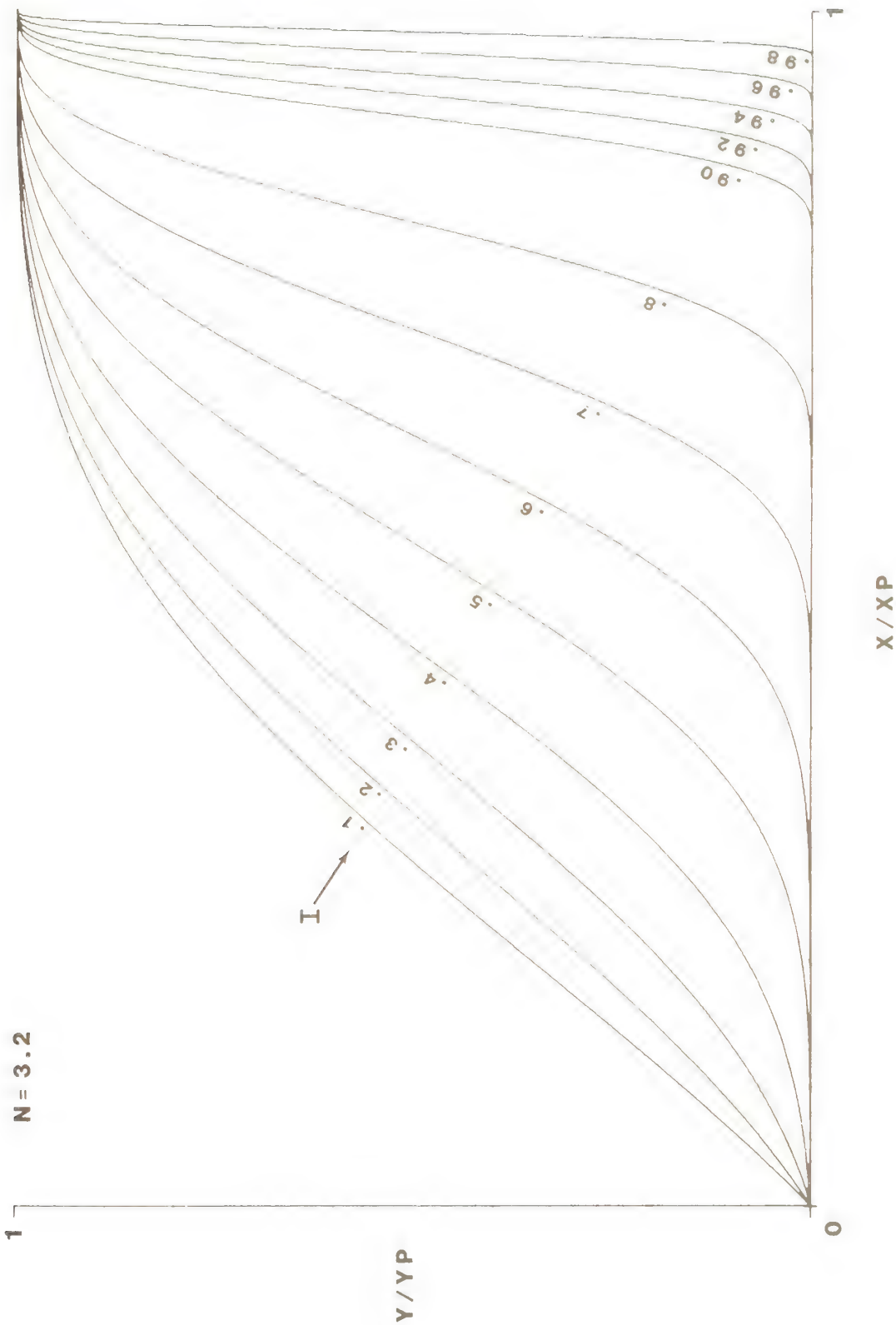

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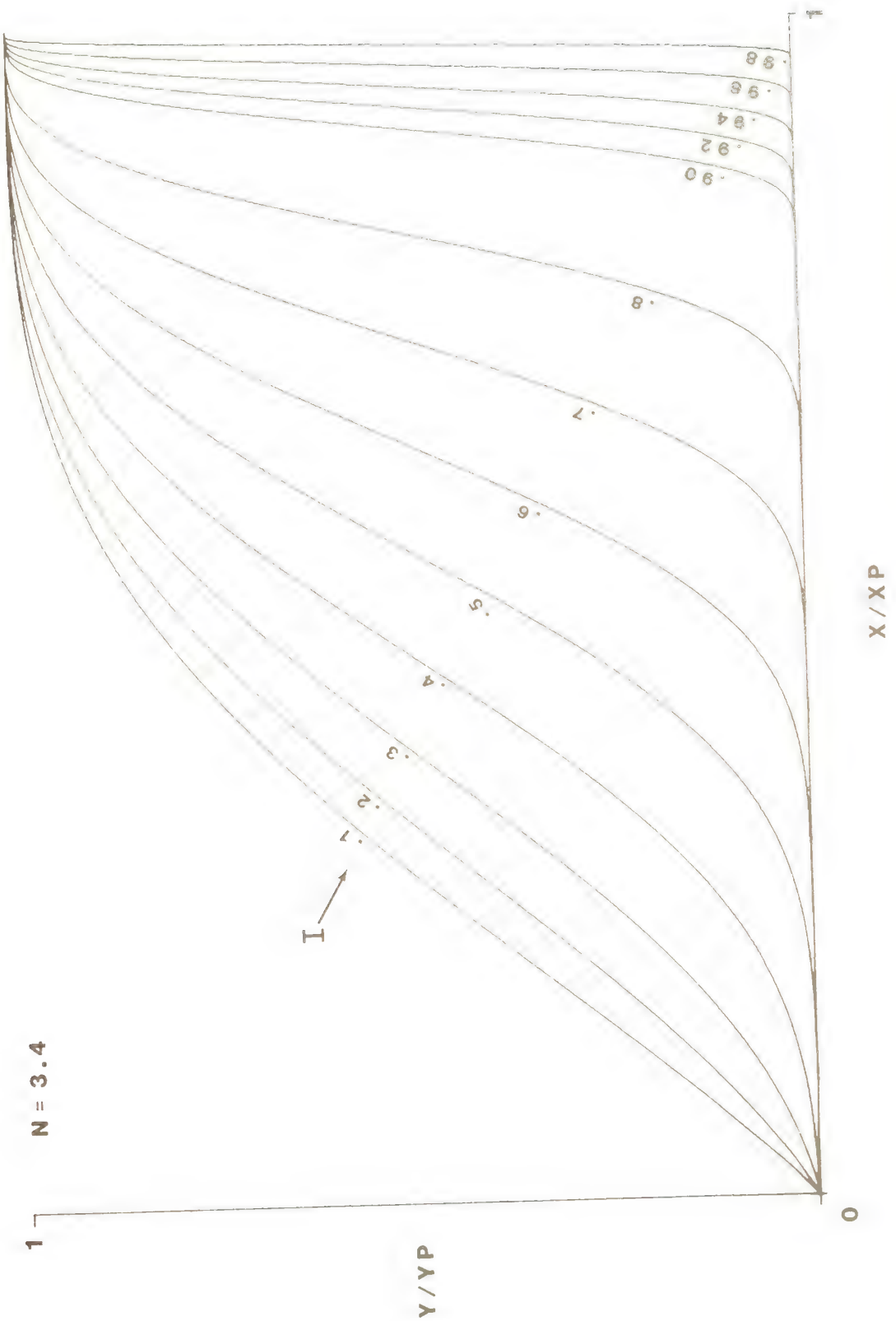

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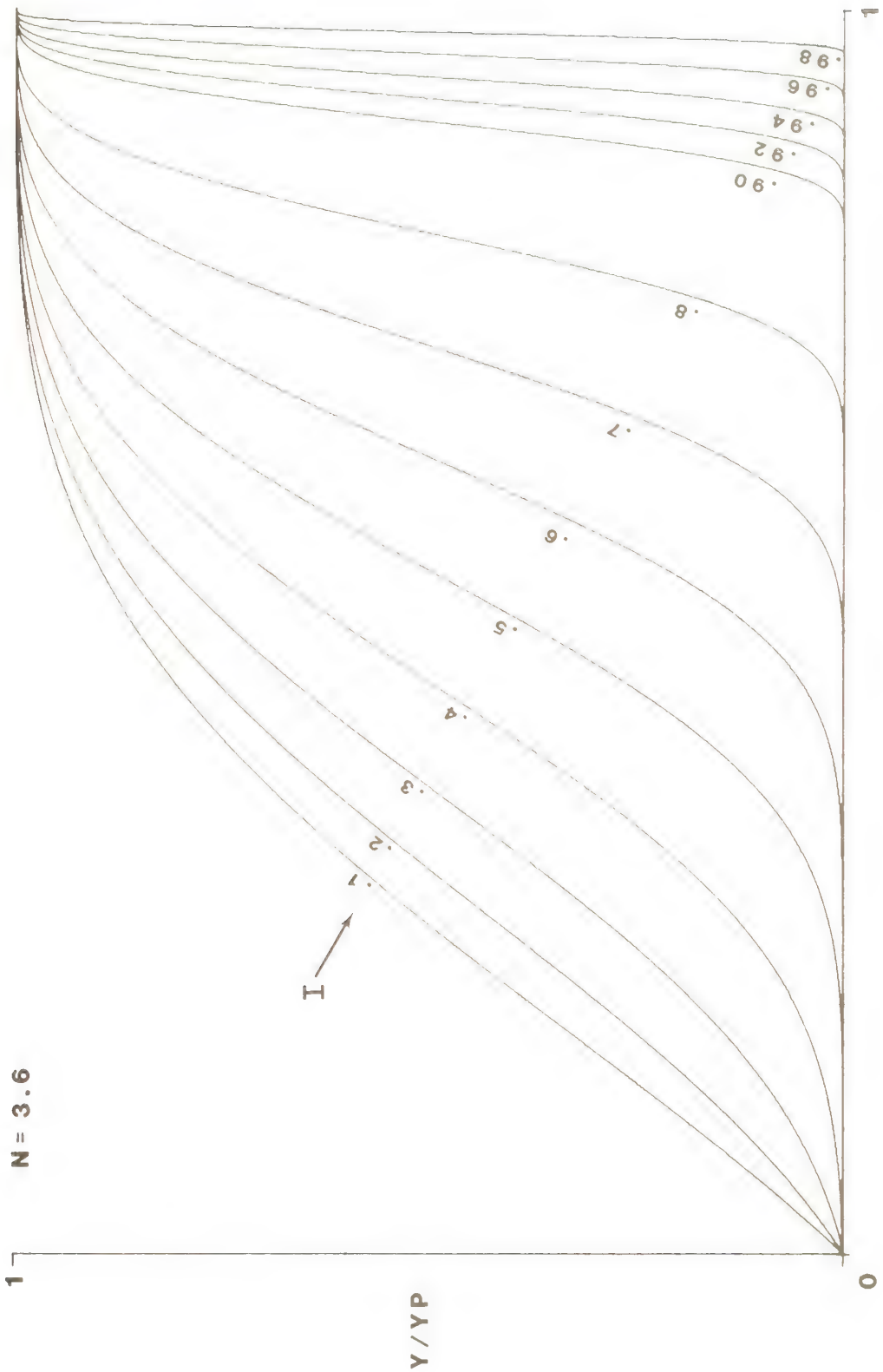

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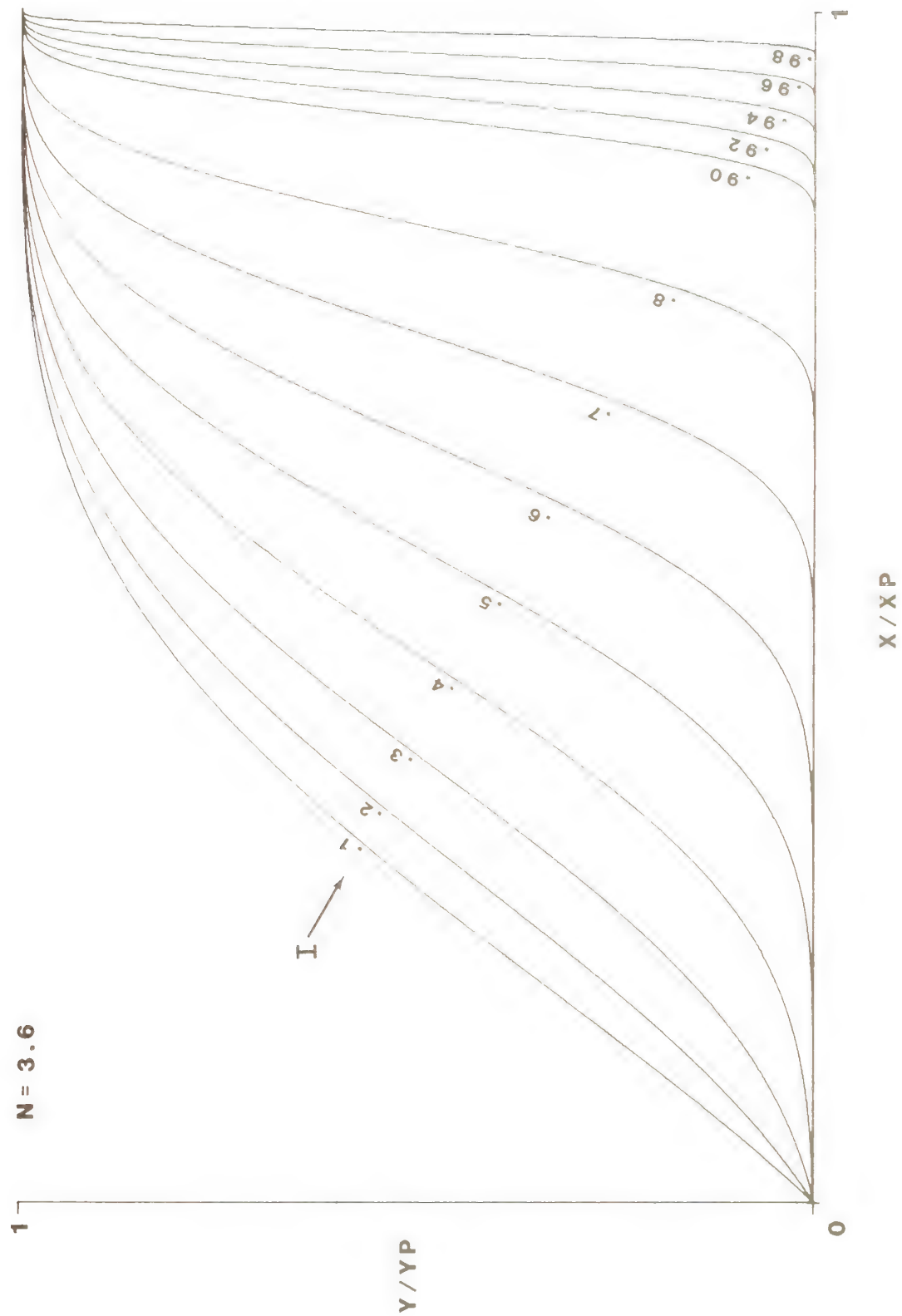

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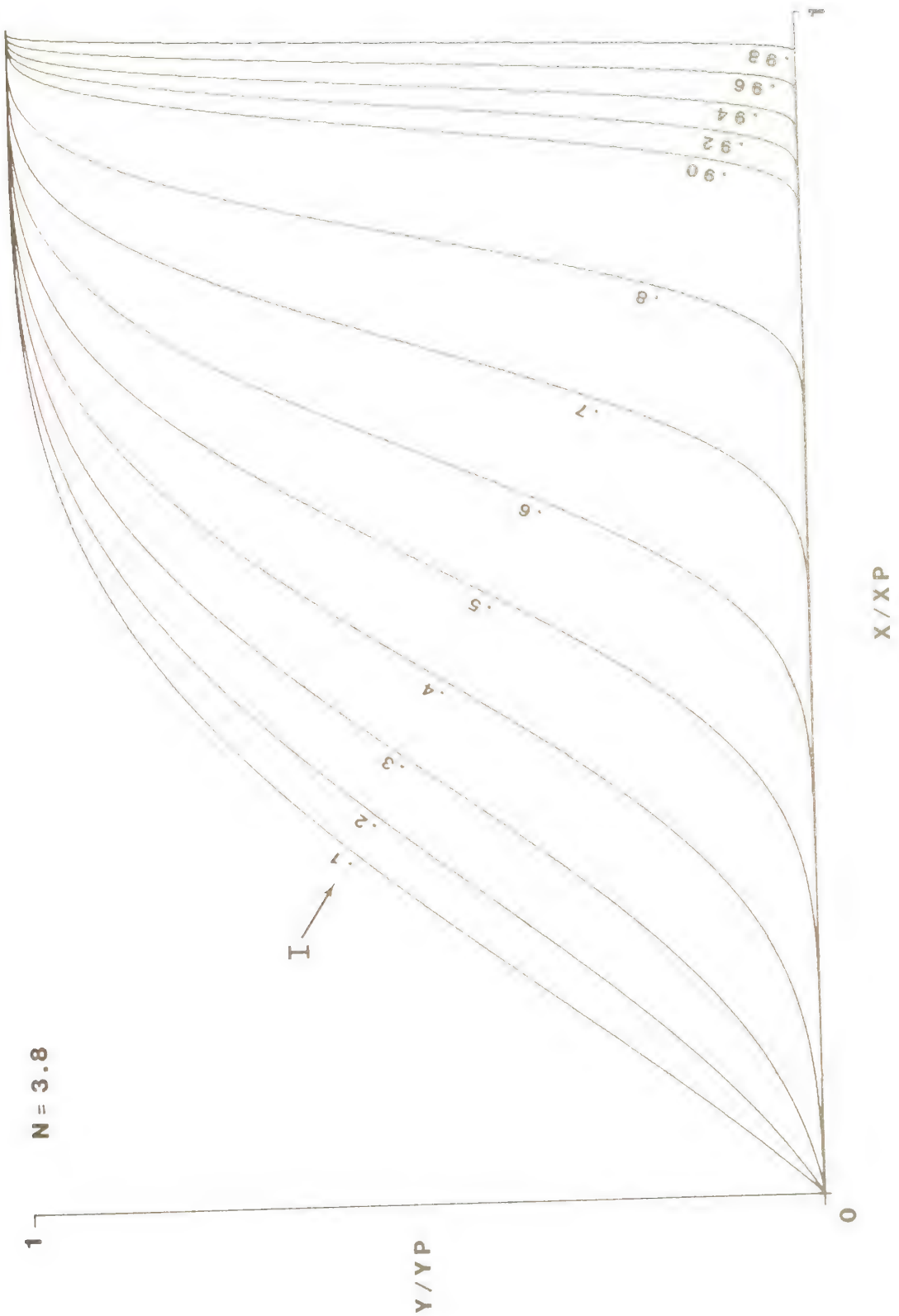

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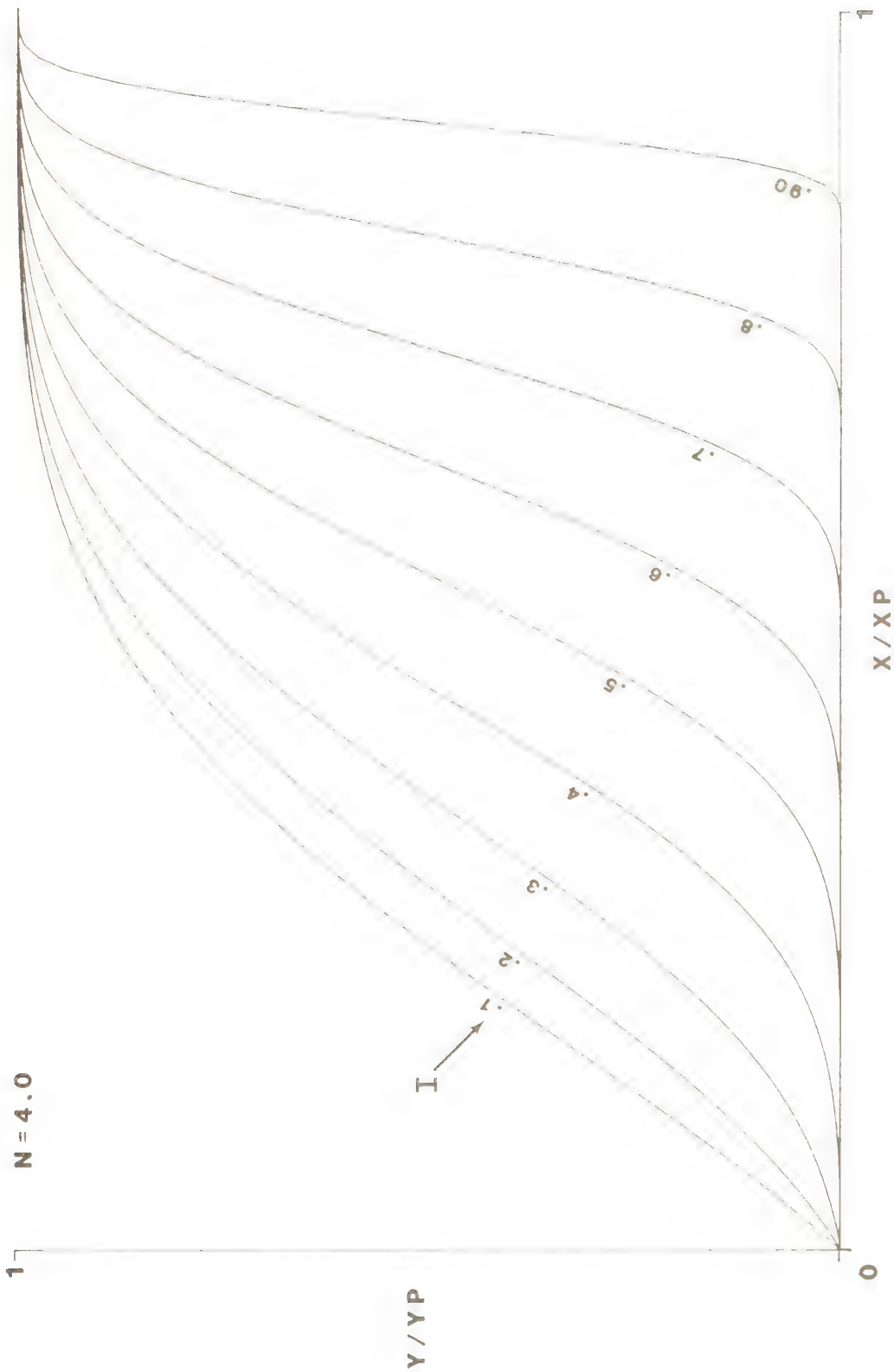

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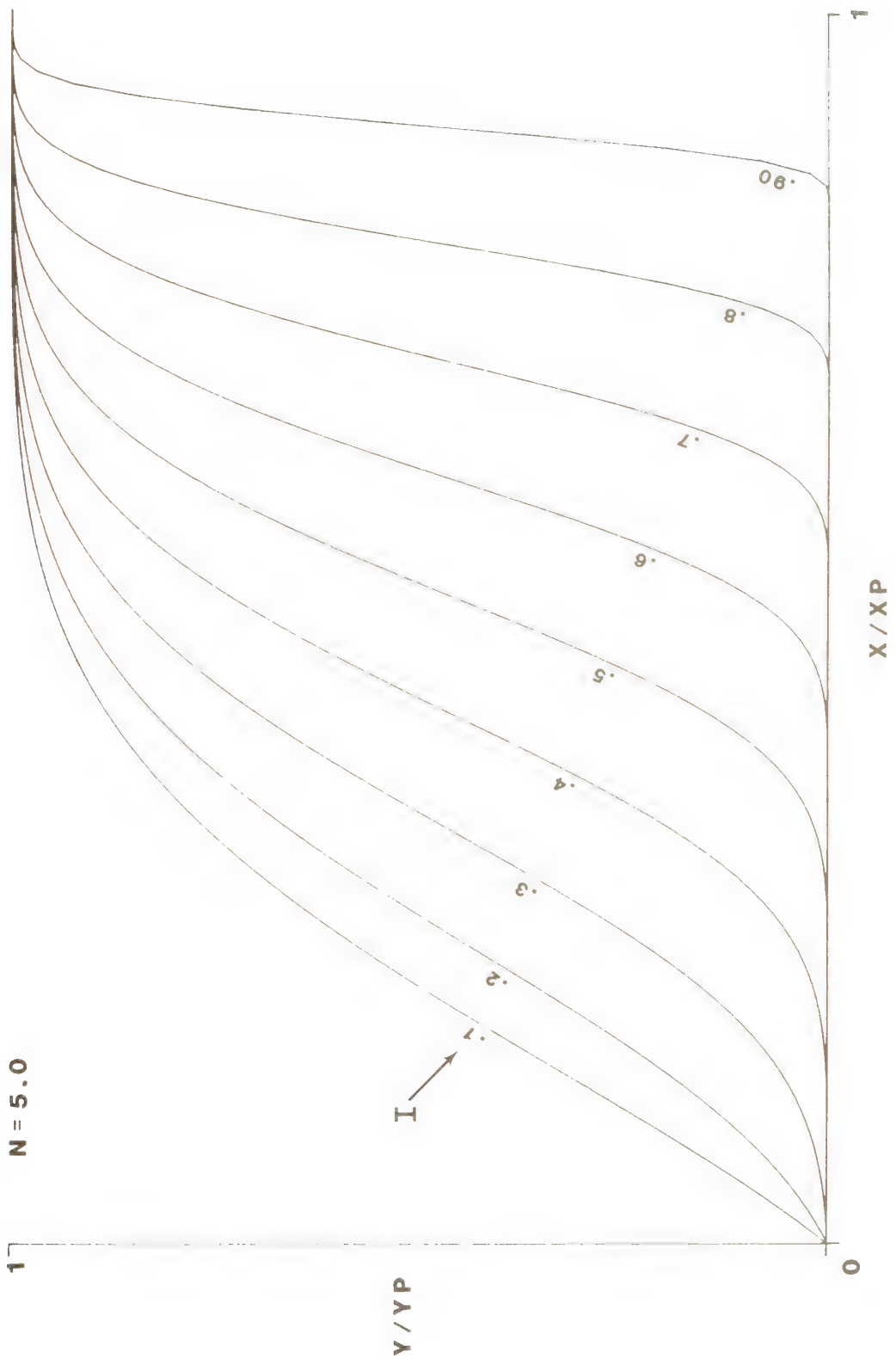

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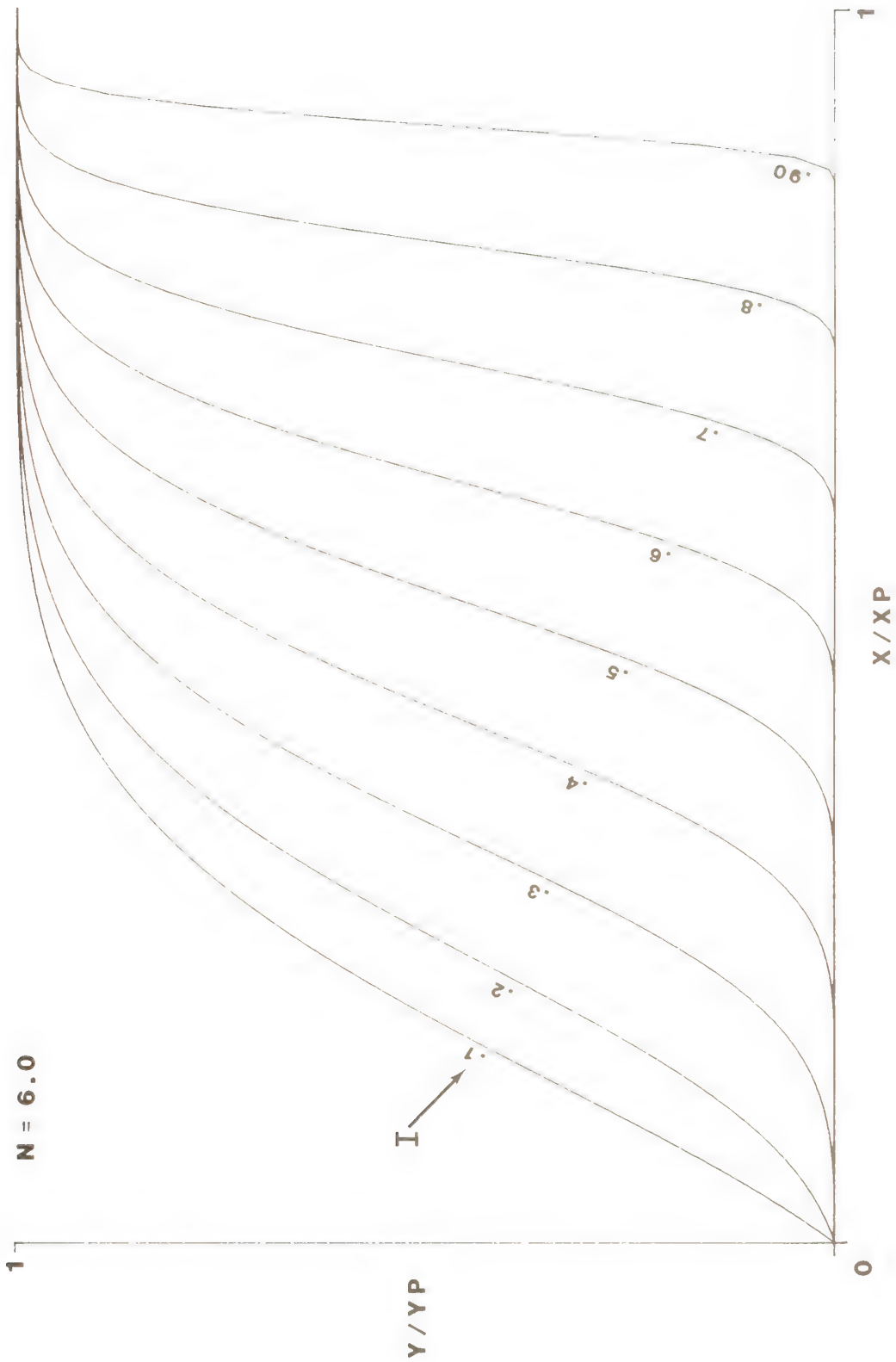

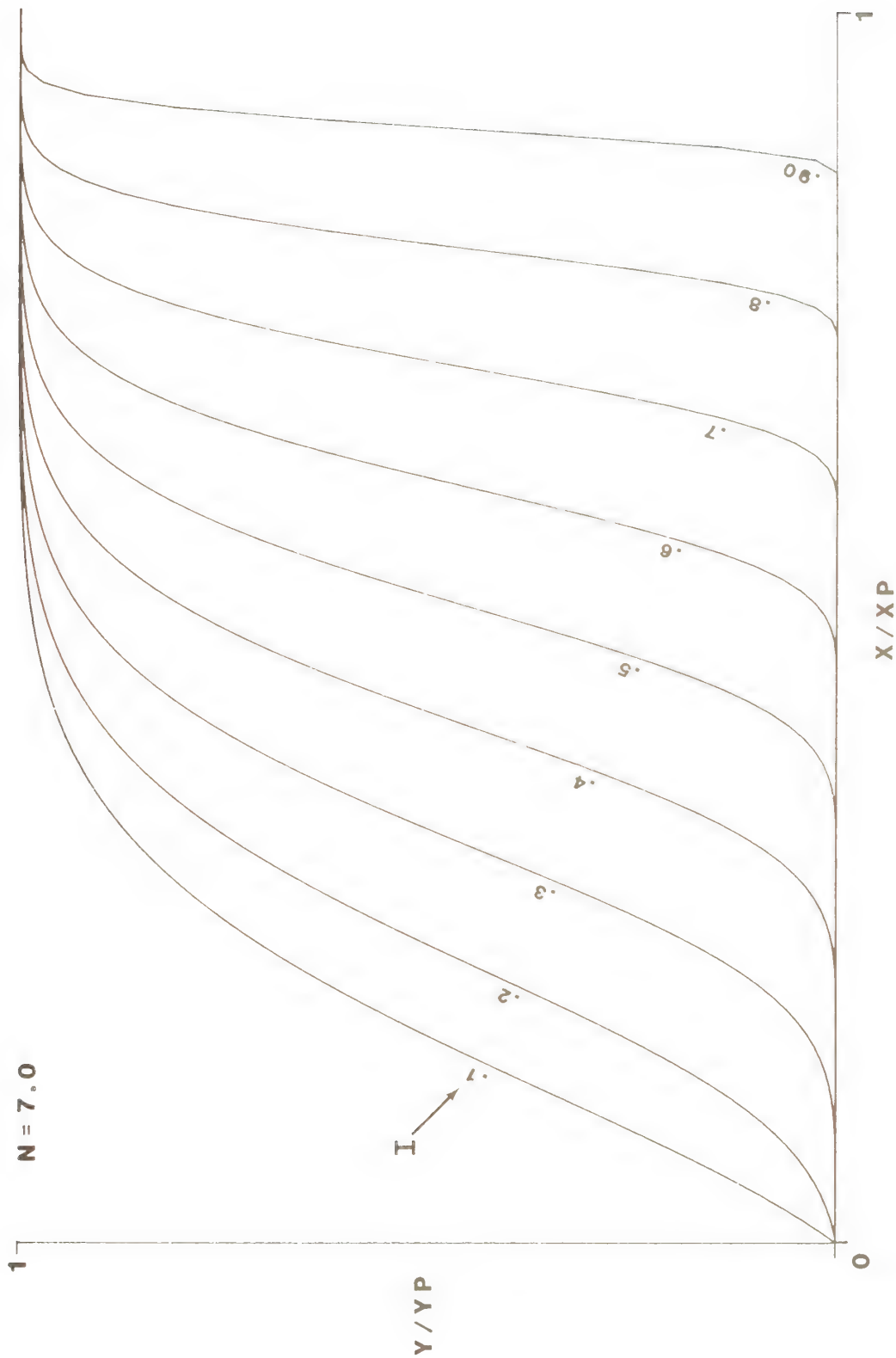
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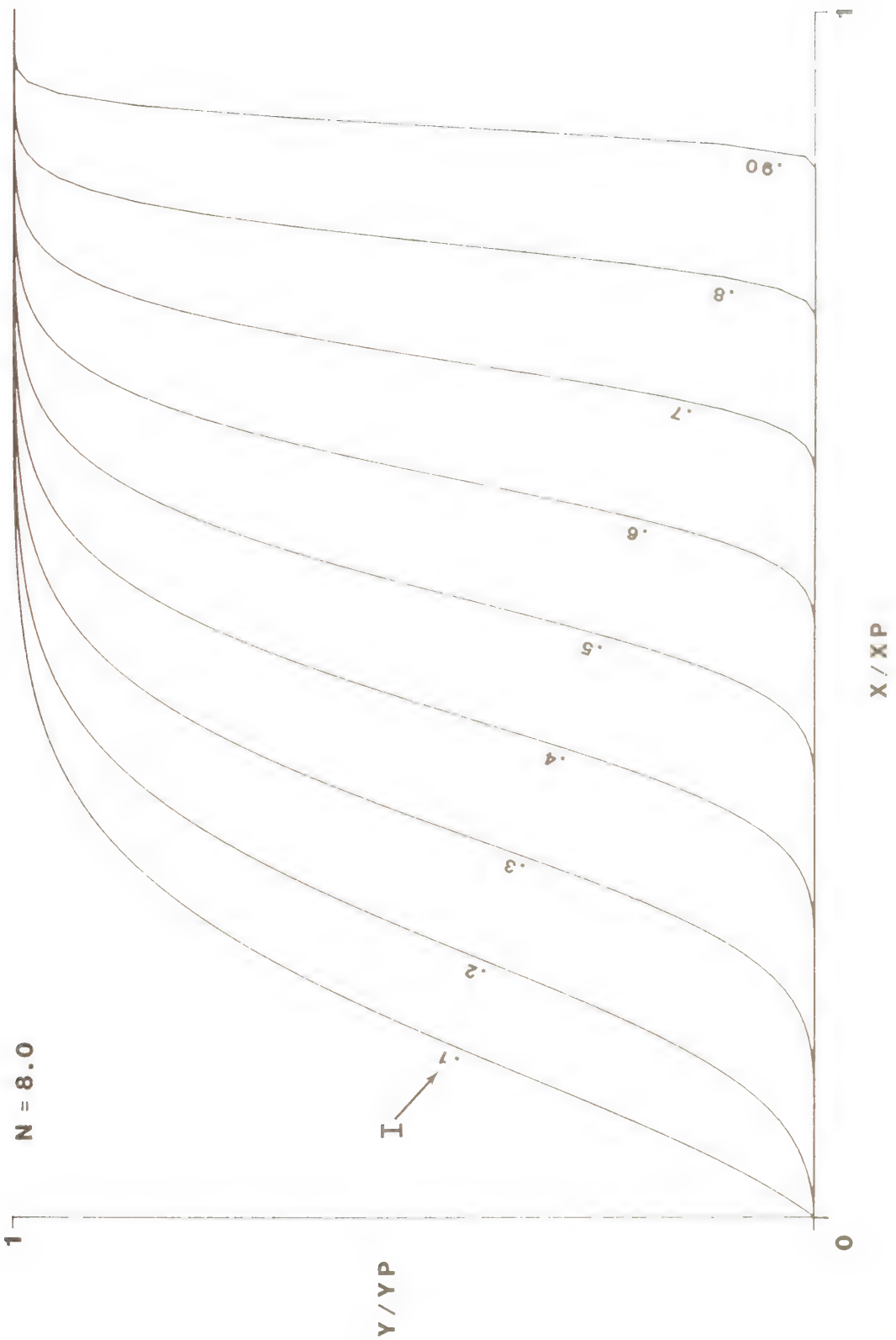

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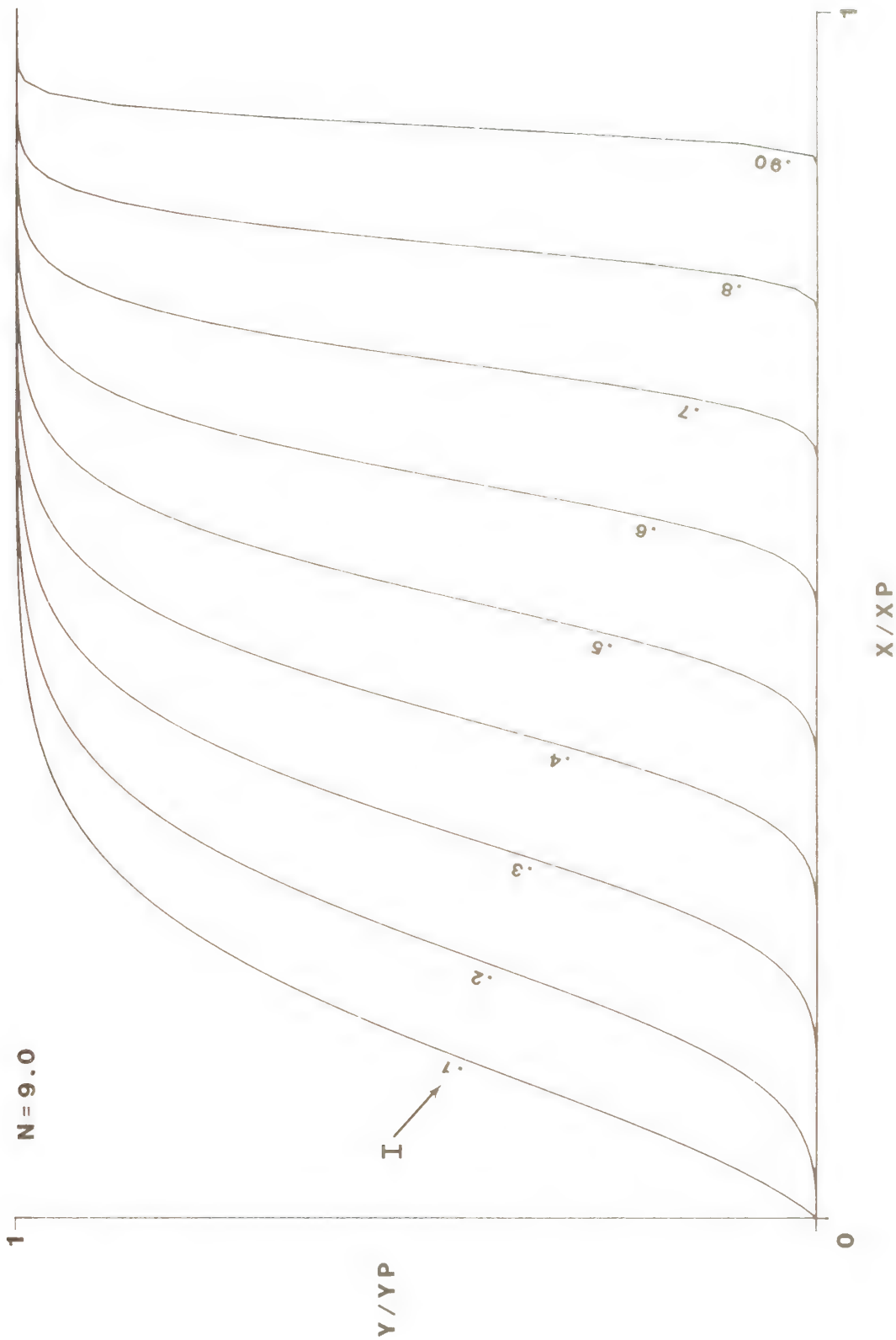

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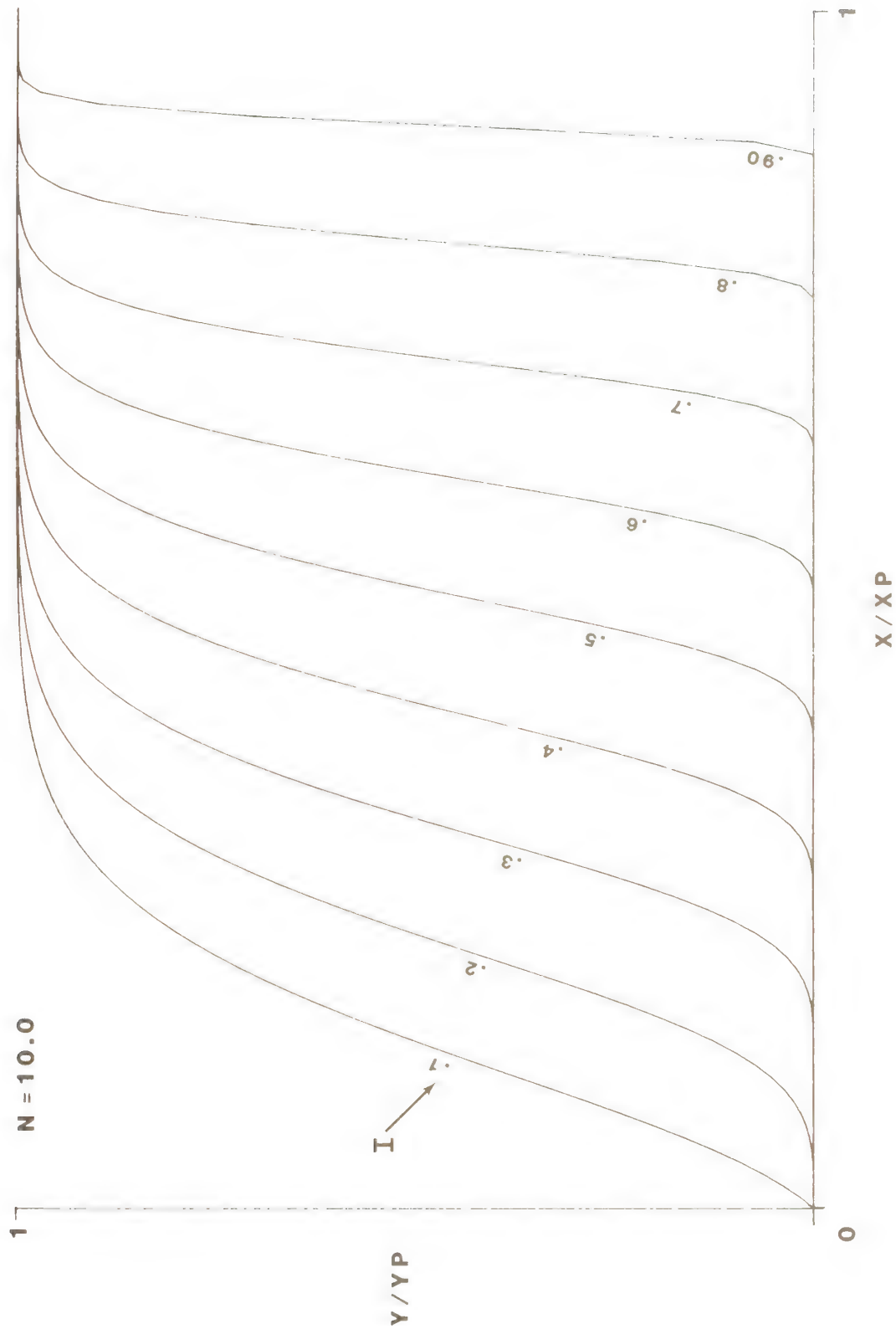

Jensen, Chester E. Development of structured regression hypotheses/interactive descriptive geometry through five dimensions. Res. Pap INT-324. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1982. 155 p.

The problem of over-simplified regression hypotheses is identified and alternatives are discussed. Methods for developing structured hypotheses, first graphically and then mathematically, are shown for two- through five-dimensional cases. Mathematical formulation is accomplished through use of two families of curves: X^n, $n \geq 1$, and e^{-K}, a highly manipulable function for bell shaped curves or portions thereof.

KEYWORDS: structured regression hypotheses, regression hypotheses, modeling, interactive models, multidimensional descriptive geometry

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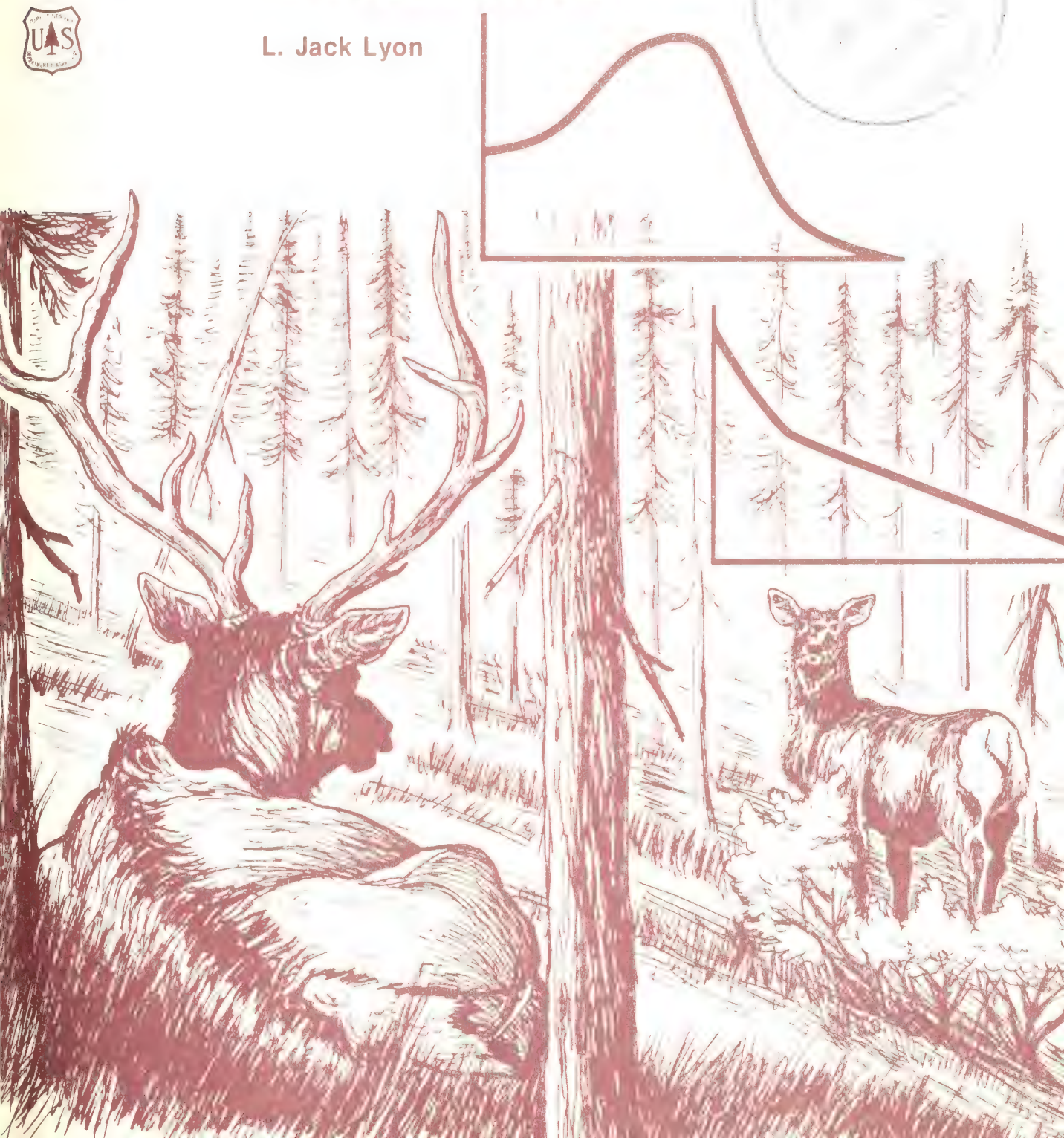
Research Paper
INT-325

February 1984

Field Tests of Elk/Timber Coordination Guidelines

L. Jack Lyon



THE AUTHOR

L. JACK LYON, wildlife research biologist, is leader of a research work unit devoted to the ecology and management of forest wildlife habitats. The unit is headquartered at the Forestry Sciences Laboratory on the campus of the University of Montana. Dr. Lyon holds B.S. and M.S. degrees in wildlife management from Colorado State University and a Ph.D. in the same field from the University of Michigan. He has authored over 50 technical publications and articles. He is life member of The Wildlife Society and a member of the American Institute of Biological Sciences, Society for Range Management, and Ecological Society of America.

ACKNOWLEDGMENTS

In all, 46 observers participated in the fieldwork for this study. I am particularly indebted to Thomas O'Neil in 1980 and Leonard Young in 1981. O'Neil successfully completed and defended a master's thesis (O'Neil 1981) based on the first year of data collection.

RESEARCH SUMMARY

During recent years, conceptual models for elk habitat have been widely used as guidelines for coordinating elk habitat management and timber management. The generalized model, consisting of a cover/forage function and a road density function, has been used at the Forest and Regional level for planning required by the Resources Planning Act. In addition, several management biologist teams have developed specific models that recognize local variations in elk behavior. At the present time, despite the wide acceptance and use of the elk/timber guidelines concept, variations in application and calculation methods are common. The many forest biologists and land managers who make decisions based on elk/timber guidelines require confirmed validation of the model.

During the summers of 1980 and 1981, field validation tests were conducted in 11 different areas in Montana and northern Idaho. The objectives of this research were (1) to evaluate several common methods of determining cover/forage ratios, (2) to evaluate several different road-influence models, and (3) to determine the combination of cover/forage function and road model that best describes actual elk selection among different available habitats.

Comparison of on-the-ground cover samples with several indirect methods for determining cover demonstrated that indirect methods generally overestimate actual cover. A reliable indirect method for using photo interpretation (PI types) is presented. Comparison of several different road-influence models demonstrated that predictions and accuracy vary considerably. Acceptable models and precision limits are described. Evaluations of elk habitat quality based on different combinations of cover/forage function and road models were compared to actual habitat selections as indicated by elk pellet group distributions. Findings show that within the range of cover values tested, elk response to habitat quality is primarily determined by road densities. Acceptable road models predict over 50 percent of the variation in habitat use by elk. The best of the cover/forage functions tested improved this prediction on only half the validation areas, and then by less than 10 percent.

In the concluding discussion, it is suggested that a more comprehensive habitat model will be required to provide a valid test of the simple cover/forage functions now being used. Specifically, such a model must account for changes in cover requirements over time.

Field Tests of Elk/Timber Coordination Guidelines

L. Jack Lyon

INTRODUCTION

Two papers describing preliminary models for coordinating big game habitat management with timber management in the Blue Mountains of Oregon and Washington were presented in 1976 (Black and others 1976; Thomas and others 1976). Soon after, similar models for elk/timber coordination were developed throughout much of the West.

As additional research was completed, habitat models were expanded to include the influence of forest roads and traffic on elk use of the available habitat. By 1979, Thomas and others had developed a more sophisticated model to predict habitat potential as a function of cover/forage ratios and habitat effectiveness as a function of road densities (Thomas and others 1979).

As this work proceeded in Oregon, teams of biologists from State game and fish departments, the USDA Forest Service, and usually from several other agencies, have cooperated in developing elk/timber coordination guidelines for the East-side and Central Zone Forests in Montana, for northern and south-central Idaho, and for the Bitterroot, Kootenai, Bridger-Teton, and other National Forests. Considering the speed with which these models were accepted, modified for local application, and applied in land management, it is not surprising that some guidelines have been interpreted inconsistently. Differences have been further emphasized by continuing research that has modified some guidelines almost annually.

Although there is no valid reason to assume that all elk in all situations will respond to environmental modification in the same way, it was nevertheless considered desirable to conduct a field validation test of existing models to determine what standardization is possible and whether the models do, in fact, predict elk behavior in a variety of environments. Accordingly, field validation tests of elk timber coordination guidelines were conducted on 11 study areas in western Montana and northern Idaho during the summers of 1980 and [illegible]. The test hypothesis was that adjacent areas equally available to the same elk would be used by those elk in the proportions predicted by the guidelines.

STUDY AREAS

Study areas were recommended by local biologists within the limitations of the following criteria:

1. Area has a stable elk herd in a productive habitat.
2. Study area can be subdivided into three or four adjacent and topographically similar subunits.
3. All subunits must be equally available to the same elk.
4. No logging or other unusual major disturbance has occurred on the area within the last 2 years.

Areas with recognizable differences in road densities and cover among subunits were preferred. Table 1 and the following narrative briefly describe each of the 11 study areas.

Table 1.—Summary descriptions of 11 study areas

Area	Sub-units	Acres	Hectares	Forest	Average elevation		Trees[1]
					Feet		
Skalkaho	4	8,774	3 553	Bitterroot	7,600	2 317	ABLA-PICO
Blue Mountain	3	10,870	4 402	Lolo	5,200	1 585	PSME
Jim Creek	4	8,978	3 636	Flathead	4,800	1 463	THPL-ABLA
Beaver	3	10,701	4 334	Kootenai	4,700	1 433	TSME-ABLA
Petty	4	12,901	5 225	Lolo	5,300	1 615	PSME-PICO
Bateman	3	8,666	3 510	Lolo	5,400	1 646	PSME
Hyalite	4	16,843	6 821	Gallatin	7,100	2 164	ABLA-PICO
Judith	4	15,445	6 255	Lewis & Clark	6,800	2 073	ABLA-PICO
Red Ives	3	7,844	3 177	St. Joe	5,300	1 615	TSME-ABLA
Canyon	3	8,547	3 462	Clearwater	4,500	1 372	THPL-ABGR
Newsome	3	8,165	3 307	Nezperce	5,200	1 585	THPL-TSHE

[1]Although habitat types (Pfister and others 1977) were recorded, the most important tree species provide a broader description for this table: ABLA, *Abies lasiocarpa*; PICO, *Pinus contorta*; PSME, *Pseudotsuga menziesii*; THPL, *Thuja plicata*; TSHE, *Tsuga heterophylla*; TSME, *Tsuga mertensiana*; ABGR, *Abies grandis*.

Skalkaho.—The Skalkaho study area is located 15 miles (24 km) east of Hamilton, Mont., in the Sapphire Mountains. It lies entirely within the Skalkaho Game Preserve, which is closed to big game hunting. Logging has taken place in two of the subunits. The other two subunits are completely unroaded.

Blue Mountain.—The Blue Mountain area is 7 miles (11 km) west of Missoula, Mont., in an area that has been moderately to heavily logged. All three subunits are accessible in some degree by way of old logging roads.

Jim Creek.—Jim Lake, located in the southernmost subunit of the Jim Creek area, is a popular and easily accessible recreation site 5 miles (8 km) northwest of Condon, Mont. All four subunits border the Mission Mountain Wilderness, and logging has taken place in three of the subunits.

Beaver.—This study area is located at the headwaters of Big Beaver Creek, 14 miles (23 km) southwest of Trout Creek, Mont. All three subunits have been logged to some degree.

Petty.—This study area consists of four nearly parallel drainages to Petty Creek. It lies 27 miles (43 km) west of Missoula, Mont. Three drainages have been logged in recent years; the fourth is mostly undisturbed although easily reached from existing ridgeline roads.

Bateman.—The Bateman study area runs from Burnt Mountain to Bateman Creek on a north-facing aspect above the Clark Fork River, 24 miles (39 km) east of Missoula, Mont. Three subunits range from heavily logged and roaded to inaccessible, although all three have been logged.

Hyalite.—The four subunits of the Hyalite study area include both sides of Hyalite Canyon about 8 miles (13 km) south of Bozeman, Mont. All four subunits have been logged, but many of the logging roads are closed to vehicular traffic and much of the recreational use occurs near the valley bottom.

Judith.—The four subunits of the Judith study area lie on both sides of Deadhorse Creek in the Little Belt Mountains about 25 miles (40 km) northeast of White Sulphur Springs, Mont. All four subunits have been logged, and road densities are relatively high throughout the area.

Red Ives.—The Red Ives study area is located 50 miles (80 km) east of St. Maries, Idaho, on the divide between the St. Joe and Clearwater Rivers. Two of the subunits have been logged, and all three are accessible from a road running along the divide.

Canyon.—This study area is located 10 miles (16 km) north of the junction of the Lochsa and Selway Rivers in northern Idaho. Two of the three subunits have been logged, one very heavily, and the third is accessible only from a ridgeline road.

Newsome.—Although four subunits were sampled on this study area 15 miles (24 km) northwest of Elk City, Idaho, only three proved to be comparable. Of these, two have been logged and one is essentially undisturbed

DATA COLLECTION

Within each subunit, 5 to 15 miles (8 to 24 km) of belt transect were sampled to determine elk use. Observers walked a designated course, usually on contour at a specified elevation, and recorded all pellet groups in an area 2 feet (0.6 m) on either side of the path. Pellet groups were classified as fresh, new, old, or very old on the basis of color and stage of deterioration. Groups were recorded by age class within variable length segments along the transect. Segments were separated at any point where a change in aspect or stand condition was noted. Observers sampled each subunit on at least two transects separated by 200 to 500 vertical feet (61 to 152 m).

In addition to recording pellet groups, observers evaluated the elk habitat on each segment and classified it as hiding cover; thermal cover; forested forage; open forage; or nonhabitat, such as rockslides and open water.

After the collection of field data, each area was mapped using aerial photographs and Forest Service photo interpretation (PI) maps. PI types were planimetered and mileages measured for primary, secondary, and primitive roads within each subunit. Comparative data for the 11 study areas are presented in table 2.

PRELIMINARY ANALYSES

Elk Use

Estimates of elk use in each of the subunits were derived by calculating the total area sampled on transects and dividing into the sum of the pellet groups recorded. All pellet groups judged to be very old were deleted from this analysis. Densities ranged from a low of 1.7 groups per acre (0.7/ha) in the Jim Lake subunit of the Jim Creek study area to a high of 179.2 (72.6/ha) in the Falls Creek subunit of the Skalkaho (table 2).

Statistical evaluation of differences among transects, observers, and subunits requires an estimate of variance within samples. This estimate was calculated by treating each transect segment as a single observation, even though segments were not of equal length. The resulting analysis overrepresents short segments in the calculation means, but variance estimates are considered representative of true variance for sample means (table 3).

Observers

In all, 46 observers participated in this study; however, only 8 observers walked more than 2 transects and only 3 walked more than 10 transects. In most cases, it was necessary to assume that variations among observers represented actual variation among transects. One observer, however, recorded only a single pellet group on a transect in the Hyalite study area, and since

e 2.—Comparative data for 38 subunits in 11 study areas[1]

dy area / subunit	Acres	Transect miles	Pellet groups[2]			Pellet groups per acre	Miles of road			Miles per section[3]	
										Total	Rated
kaho											
alls Creek	2,813	11.4	68	501	425	179.2	0	0	0	0	0
ttle Burnt	2,103	10.2	25	428	350	170.0		0	0	0	0
am	1,888	8.7	15	209	234	108.8	0	5.7	0	1.9	1.4
rooked	1,971	7.4	17	146	161	90.9	3.1	0	1.4	1.5	1.0
e Mountain											
oodman	3,720	14.0	12	52		15.9	0	3.8	2.9		.5
eeman	4,074	11.7	8	27	52	15.4	1.1	2.4	0	.5	.4
amp	3,077	10.6	3	11		5.3	0	5.9	2.7	1.8	.9
Creek											
per Crow	1,498	4.7	2		9	10.4	1.3	0	0	6	.6
oore	2,751	5.7				9.1	2.9			7	.7
ookout	1,979							0	0	.3	.3
m Lake	2,750	6.0		3	2	1.7	5.8	7.3	2.5	3.6	2.6
ver											
outh Dixie	4,497	6.6		71		43.4		1.1		1.1	.9
reen	3,005	9.5	28	54	73	33.8		3.7	5	3.0	2.6
y Gulch	3,199	7.6			39	24.3	4.3	1.8	9	1.4	1.1
y											
ds Creek	4,311	13.1		112		28.0	1.6	4.0	0	.8	6
ohns	2,264	8.2		44		25.7	9		9		5
us Creek	2,424	9.0		21	84	24.1	0	2.0	0	5	4
outh Fork	3,904	14.8	3	63	78	20.1		3			4
eman											
yler	2,593	9.2	3	10	43	12.5		1.9		.6	.5
ateman	2,853	13.7	3	15		11.5	0		2.8		.7
urnt	3,221	8.9	0		27	7.4	12.1		12.0		3.0
lite											
hisholm	4,554	10.2	8		72	23.8	1.9	0	1.6	.5	.3
uckskin	4,007	10.7	3		39	17.1	1.2	4.7	3.5	1.5	7
indow Rock	4,630	10.7	8	21	25	10.5			4.3	1.4	.7
anghor	3,652	10.0	5	22	14	8.5	2.1	12.3	2.3	2.9	1.9
th											
ross	4,233	11.5	6	70	89	29.7			.5	1.1	9
ghill	3,775	10.2	8	144	152	62.5		3.9	1.2	1.8	1.4
mith	3,720	9.4	3	82	165	54.9	5.2	3.8		1.6	1.4
lyde	3,717	10.4		39	40	17.3		1.9	0	1.8	1.7
Ives											
uck Light	3,421	14.4	1	21		10.7	5.2		0	1.1	1.0
oodoo	1,757	6.4	2	11		8.4	5.5	6	5.9	4.4	2.3
otted	2,666	11.9	2		11	5.2	4.1	3.0	1.6	2.1	1.5
yon											
iddle	2,747	12.5		63	105	28.5	3.1		0	.7	.7
eadman	2,392	12.0	3	29		16.5	6.0			1.9	1.8
anyon	3,409	10.6	1	7	23	6.0	15.4	5.1			3.6
some											
aldy	2,771	10.2		109	143	53.0		3.7	1.0	1.1	6
lot	2,113	7.0	6	20	116	42.1		4.1		1.2	9
ew China	3,280	13.0	22	71	97	30.2	2.0	2.6	1.4	1.2	.8

Metric conversion factors: acres X 0.405 = hectares; miles X 1.609 = km, miles/section X 0.621 = km/km^2.
Pellet groups: fresh, new, old.
Miles per section: total = primary + secondary + primitive; rated = primary + 0.7 secondary + 0.05 primitive.

Table 3.—Variance analyses for differences among transects, among subunits, and among transects within subunits (asterisk indicates probability $F < 0.05$)

Area	Transects		Subunits		Transects within subunits[1]
	No.	F	No.	F	
Skalkaho	12	5.32*	4	4.91*	2
Blue Mountain	9	5.22*	3	4.58*	1
Jim Creek	8	4.25*	4	7.86*	None
Beaver[2]	8	1.52*	3	4.25*	None
Petty	11	5.84*	4	1.83	2
Bateman	7	3.88*	3	.78	1
Hyalite	8	5.37*	4	5.65*	2
Judith	12	2.83*	4	2.52*	2
Red Ives	12	1.22	3	1.51	None
Canyon	10	6.51*	3	11.18*	1
Newsome	9	4.08*	3	2.69*	1

[1]Number of subunits in which significant differences among transects were detected.
[2]Two transects deleted because of significant winter range use.

two other observers on adjacent transects averaged 17 pellet groups per acre (6.9/ha), this data set was not used. In addition, one observer on the Petty study area consistently recorded two to three times as many pellet groups as observers on nearby transects. In this case, since results of subsequent analyses were similar using adjusted or unadjusted data, the unadjusted records were used.

Transects and Subunits

In preliminary analyses, significant differences among transects were detected on all but the Red Ives study area (table 3). There were only three study areas in which significant differences were not detected among subunits, and three with no significant differences among transects within subunits. For the most part, these differences were assumed to indicate differences in elk distribution that were related to habitat quality. The initial analysis, however, also demonstrated strong elk responses that were unrelated to the fairly simplistic model of habitat quality tested in this study. In two cases where elk response to extraneous factors could be clearly identified, data were either deleted or restructured.

In the Judith study area, for example, the selection criterion requiring all subunits to be equally available to the same elk was not satisfied. Two subunits north of the Judith River had 2.45 times as much elk use as the two subunits south of the river. Pellet group density estimates were adjusted upward in the two southern subunits to reflect this difference. In the South Dixie subunit of the Beaver Creek study area, five transects demonstrated a strong gradient to high winter range use at lower elevations. In this subunit, data from the two low-elevation transects were deleted from further analysis.

Cover/Forage

Preliminary analyses also required calculation of cover/forage ratios in each of the subunits. Determining cover values has been particularly difficult because management biologists rarely have the luxury of conducting on-the-ground sampling as done in this study. Instead, cover values are usually derived from photo interpretation data or timber stand inventories. Stand inventories were not available for this study, so analysis was limited to evaluation of PI types.

For each study area, field observations in PI types were summarized to obtain locally applicable conversion percentages. On the Judith study area, for example, observers encountered PI type 11 113 times and classified it as cover 51 times, which meant 45.1 percent of the PI 11 acreage was considered cover.

In addition to calculations based on individual study area data, two indirect rules for determining cover were developed and tested. Observations from all Idaho study areas were combined in one set, and observations from the more xeric lodgepole and Douglas-fir types in Montana in a second set, to obtain, respectively, the Idaho and Montana Rules (table 4). And, finally, several arbitrary assignment rules that assume certain PI types to be cover were evaluated. A complete presentation and discussion of these methods is not necessary here because most were found to be unsatisfactory. Any arbitrary assignment rule that classifies PI 11 and 14 as cover will overestimate cover values in most areas.

Best estimates were derived by using the Montana Rule for more xeric study areas and the Idaho Rule for more mesic study areas. Using the percentage conversions presented in table 4, the average cover estimate for Montana Rule areas was 46.5 ($\pm$ 1.0), $n = 22$ and for Idaho Rule areas, 66.9 ($\pm$ 2.2), $n = 17$. These estimates compare to observer averages of 46.2 ($\pm$ 2.8) and 66.7 ($\pm$ 2.7). Table 5 presents cover values for individual subunits.

Table 4.—Average percentage cover[1] for PI types, Montana Rule, and Idaho Rule

PI type	Montana Rule			Idaho Rule		
	Cover	Hiding/thermal[2]		Cover	Hiding/thermal	
11	58	41	17	82	51	31
12	38	29	9	85	65	20
13	31	22	9	46	46	0
14	63	45	18	79	64	15
15	45	45	0	64	39	25
16	34	28	6	58	53	5
17	57	33	24	65	52	13
18	39	34	5	50	45	5
19	38	30	8	50	50	0
20	30	20	10	25	25	0
21	36	16	20	30	30	0
22	30	30	0	30	30	0
23	50	50	0	50	50	0
24	30			30		
25	50			30		
26	15			15		
27	50			50		
28	33			30		
29	12			15		
30	22			20		
31	36			35		
32	23			21		
33	7			4		
40	56			40		
60	14			14		
91	15			15		
93	10			10		

[1]Based on the percentage of times reported as cover in field observations. For a few PI types, values are arbitrarily assigned because of small sample sizes.
[2]Hiding/thermal percentages are indicated for those PI types in which some trees are tall enough to satisfy the thermal cover definition (over 40 feet [12.2 m]).
[3]Any cover recorded in PI types 22-93 was considered to be hiding cover.

Table 5.—Cover percentages in subunits as determined by observers on the ground and by indirect estimates based on Montana and Idaho observer averages applied to PI types

Area	Observers				State PI rules			
Skalkaho	47.1	52.1	41.5	40.0	45.8	49.7	40.3	39.4
Blue Mountain	55.4	54.5	52.8		48.6	48.7	51.2	
Jim Creek	75.8	85.7	70.6	49.6	70.5	78.8	64.6	47.8
Beaver	67.8	68.7	57.9		64.2	65.0	55.8	
Petty	64.7	61.6	61.5	46.8	55.0	54.1	53.1	42.4
Bateman	18.8	20.5	17.2		46.5	45.3	39.8	
Hyalite	52.3	53.0	55.7	53.5	40.0	46.1	42.9	46.0
Judith	45.6	37.8	38.3	44.8	52.0	43.1	43.1	50.0
Red Ives	61.0	61.5	59.3		67.4	71.3	70.9	
Canyon	76.5	68.0	45.2		73.5	71.0	48.5	
Newsome	66.2	67.0	87.9		69.9	68.2	78.0	

Examination of table 5 shows that the State PI rules usually produce estimates of cover within 10 percent of on-the-ground sampling estimates. Only the Bateman study area deviated greatly. Nevertheless, it is clear that local sampling should supplement and modify indirect conversion of cover percentages. In particular, PI types 11 and 14 should be sampled where they constitute a large proportion of available habitat.

VALIDATION ANALYSES

Following the preliminary summary analyses, cover and road density data were used as indicated in a generalized model of the elk habitat guidelines to predict elk habitat quality for each subunit. All analyses were duplicated using the cover values determined by observers and the cover values derived from State PI rules. There were only minor differences in results from these two analyses, but because management biologists are almost always restricted to indirect methods for determining cover, only the State PI analysis is presented in this report.

Habitat Potential

According to the hypothesis proposed by Black and others (1976), the relationship between cover and foraging areas determines habitat potential for elk. Cover is defined as: thermal cover when 40 feet (12.2 m) tall with average crown canopy >70 percent; or hiding cover when it will hide 90 percent of an elk at <200 feet (61 m). Forage is defined as: forested forage when forested, but not classified as cover; or open forage when the area is without trees. Both thermal cover and hiding cover are required by elk, and all areas not classified as cover become foraging areas by default. A forest area with a cover surplus can be improved for elk if cover is removed until an optimum ratio between cover and foraging area is obtained. Continued removal of cover, however, leads to a precipitous decline in habitat potential.

The initial versions of habitat management guidelines proposed a different function for each of several land types, habitat types, or both. More recent versions assume that elk movement between cover and forage areas adequately integrates available habitat as long as the size and spacing of different stands are satisfactory. For this study, evaluation was concentrated on a "Single c/f" function (fig. 1) with a theoretical potential for doubling habitat quality as cover is reduced from 100 to 40 percent and an equivalent loss in quality as cover declines from 40 to 25 percent. Several other cover/forage functions were tested, and I also tested a "No c/f" function under which all cover values were considered equally acceptable.

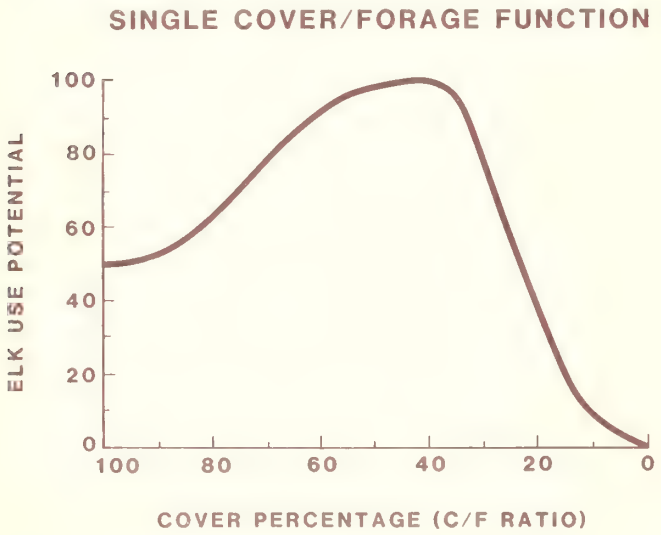


Figure 1.—Single cover/forage function.

Habitat Effectiveness (Roads)

Declines in elk use of habitat adjacent to open forest roads have been documented repeatedly (Hershey and Leege 1976; Lyon 1979; Marcum 1976; Perry and Overly 1976, 1977; Rost and Bailey 1974, 1979; Ward 1976), but only three models for evaluating the influence of road densities in elk habitat have been published (Thomas and others 1979; Lyon 1979, 1983). These models, although derived from basically similar data, differ significantly in concept and output.

The Perry-Overly model (Thomas and others 1979) contains three nonlinear functions: one for primary roads, another for secondary roads, and a third for primitive roads. In 1979, I published a cover/road model with four linear functions: one for each of four cover densities. More recently (Lyon 1983), I have used the same data to develop a model with a single nonlinear function.

In this study, I evaluated these road models, several other unpublished road models, and some alternative methods of calculating road densities. The majority of these evaluations produced unsatisfactory results, and only the published road models are evaluated here.

1. Perry-Overly (Thomas and others 1979) (fig. 2). This model uses three nonlinear functions relating the independent influences of primary, secondary, and primitive roads on habitat effectiveness for elk. The calculation method, described in Agriculture Handbook 553, assumes that declines in effectiveness are additive.
2. Linear Cover/Road-A (Lyon 1979) (fig. 3). This model uses four linear functions relating losses in habitat effectiveness to cover availability in four categories. Since the published model assumes all roads to be of the same type, the initial evaluation was calculated with road densities based on the sum of primary and secondary roads.

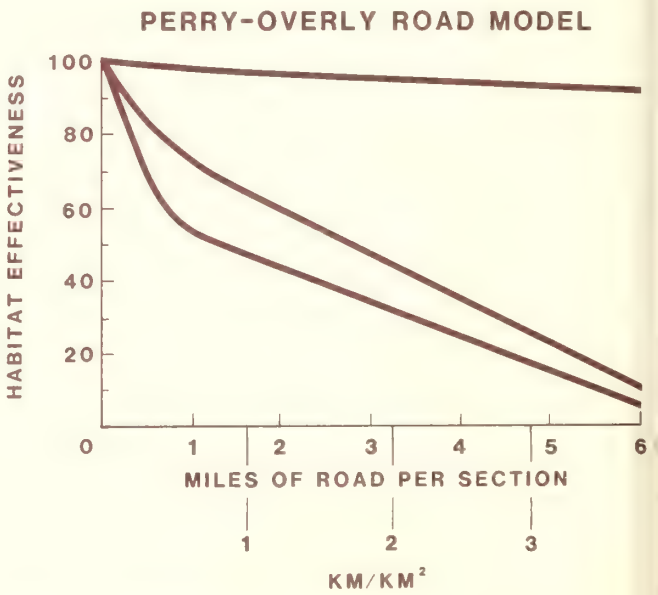


Figure 2.—Perry-Overly road model.

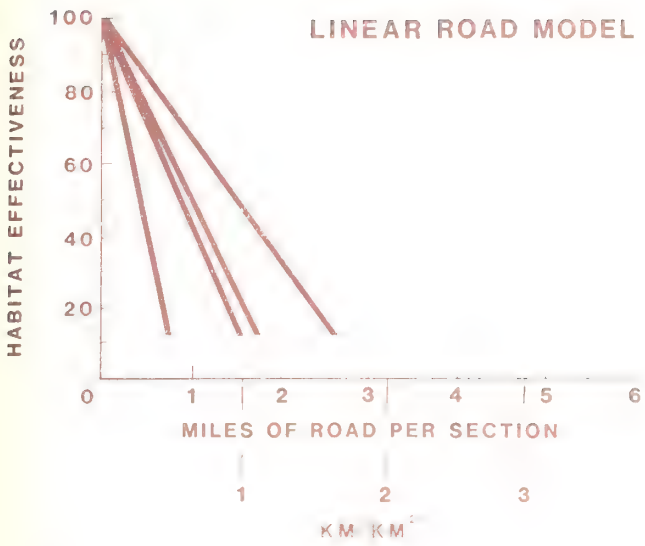


Figure 3.— Linear road model.

3. Linear Cover/Road-B. A second calculation with this model scaled road densities in proportions suggested by the Perry-Overly model: 1.00 for primary roads, 0.70 for secondary roads, and 0.05 for primitive roads.

4. Single Function-A (Lyon 1983) (fig. 4). This model projects road density influences as a single nonlinear function of the same shape as the Perry-Overly functions. In the initial calculation, road densities were based on the sum of primary and secondary roads.

5. Single Function-B. A second calculation with this model scaled road densities in proportions suggested by the Perry-Overly model.

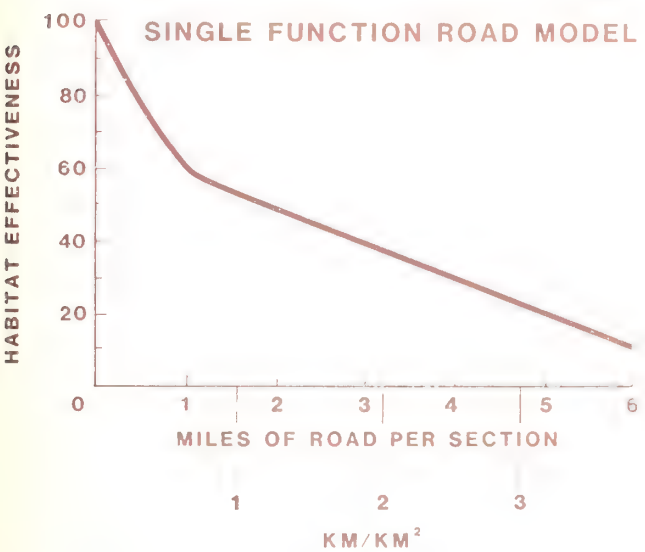


Figure 4.—Single function road model.

Habitat Evaluation

After determination of a coefficient for habitat potential (cover/forage), and a coefficient for habitat effectiveness (roads), the habitat value for each subunit was estimated as the product of the two coefficients. The test hypothesis assumes that elk use of the study area, as estimated by the sum of all pellet groups recorded, should be distributed among subunits in the proportions indicated by the habitat values. An example of a validation test is presented in table 6.

In this example, cover ranged from 40.0 to 46.1 percent and road densities from 0.28 to 1.90 miles per section (0.17 to 1.18 km/km²) among the four subunits. Coefficients for habitat potential were all close to 1.00, but coefficients for habitat effectiveness ranged from 0.85 on the least roaded subunit to less than 0.50 in the heavily roaded subunit. The products of the cover and road coefficients provide estimates of relative habitat value ranging from 0.49 to 0.85.

The sum of all pellet groups in the study area, taken to represent the elk population, was distributed among subunits in proportions indicated by habitat value coefficients. For this example, predicted pellet-group density came within 2 ½ pellet groups per acre (1.0 ha) for two subunits and within 5 per acre (2.0 ha) for the other two subunits. The mean square deviation, or variance, among the four estimates tests precision. Had the predictions agreed with measured elk use, variance would have been zero.

To complete the evaluation and allow for comparison among models, the calculated variance was divided by the average pellet group density on each study area. This standardized variance (SV = variance mean) is comparable for all study areas even where actual elk populations are far different. SV was selected instead of the more familiar coefficient of variation (CV = standard deviation mean) because the CV tended to overemphasize estimates from areas with small elk populations.

In all but two study areas, at least one combination of a cover forage function and a road model produced a deviation variance smaller than the mean (SV < 1). No tested combination produced SV < 1 on more than six areas. Table 7 presents average standardized variances for the Single c/f and No c/f functions and for three of the many road models tested. None of the other tests gave results as precise as the best of these.

The smallest average SV in table 7 has a P:0.05 confidence interval of 0.75 to 1.97. Calculation of similar confidence intervals for other SV averages confirms that estimates of habitat value using the linear cover/road model are less precise than estimates made with other road models. There were no significant differences between estimates based on the Perry-Overly and single function road models. Nevertheless, the Perry-Overly model should not be used because, in all combinations, it estimates greater losses in habitat effectiveness when primary and secondary roads are evaluated separately than when an equivalent density of primary roads is evaluated alone.

Table 6.—Representative validation test. Hyalite study area, "single c/f" and "single function-B" models with road density based o primary + 0.7 secondary + 0.05 primitive

Item	Subunit							
	Chisholm		Buckskin		Window Rock		Langhor	
Acres (hectares)	4,553.8	(1 844.3)	4,007.3	(1 623.0)	4,629.7	(1 875.0)	3,652.4	(1 47
Percent cover	40.0		46.1		42.9		46.0	
Road miles (km)								
Primary	1.9	(3.1)	1.2	(1.9)	2.0	(3.2)	2.1	(
Secondary	0		4.7	(7.6)	4.0	(6.4)	12.3	(1
Primitive	1.6	(2.6)	3.5	(5.6)	4.3	(6.9)	2.3	(
c/f coefficient	1.000		0.992		0.998		0.992	
Road coefficient	.851		.671		.687		.496	
Habitat value	.851		.665		.686		.492	
PGA actual (group/ha)	23.75	(9.6)	17.09	(6.9)	10.46	(4.2)	8.48	(
PGA estimated	18.93	(7.7)	14.79	(6.0)	15.25	(6.2)	10.95	(
	4.82	(2.0)	2.30	(.9)	4.79	(1.9)	2.47	(

Mean square = 19.19, standardized = 1.26

Table 7.—Average standardized mean square deviation and standard errors, 2 cover/forage functions, 3 road models, and 2 calculation methods[1] on 11 study areas

Road model	Cover/forage function	
	Single c/f	No c/f
Perry-Overly	1.67 (0.728)	1.53 (0.623)
Linear cover/road-A	5.80 (1.483)	5.62 (1.265)
Linear cover/road-B	5.21 (1.268)	5.16 (1.140)
Single function-A	1.60 (.384)	1.45 (.307)
Single function-B	1.56 (.409)	1.36 (.273)

[1]A, when road density = primary + secondary; B, when road density = primary + 0.7 secondary + 0.05 primitive.

Initially, the results in table 7 seemed to provide an evaluation of relative importance for cover/forage functions and road models in the habitat management guidelines. The road model alone (No c/f) predicted about 56 percent of the variation in elk use among subunits, and the addition of the cover/forage curve failed to consistently improve predictions. In retrospect, the apparent failure of the cover/forage function should have been anticipated because a majority of subunits examined in this study had cover percentages between 40 and 55 percent—a range where little difference in elk response could be expected. Moreover, cover values among subunits ranged more than 10 percent in only four of the study areas. Thus, this study was almost certain to provide a more powerful test of road effects than of cover/forage influences.

Examination of SV for individual study areas (table 8) reveals that the Single c/f did improve predictions on half the study areas but failed on the other half. For the six areas where an improvement was recorded, $r^2 = 0.63$ ($n = 20$ subunits); for the remaining five areas $r^2 = 0.19$ ($n = 18$ subunits). As a result of this observation, predictions for all study areas were examined for possible relationships correlated with cover, roads, habitat diversity (Simpson's diversity index), disturbances, seasonal habitat selection, and elk population levels.

Considering the relatively narrow range of cover values tested in most of the study areas, it was expected that the cover/forage function might have the greatest influence on those study areas with the greatest range of cover values. This did not prove to be the case. Instead, the predictions improved most on study areas where cover among subunits was most similar. Nor was there any indication that geographic location, timing of fieldwork, elk population levels, or habitat diversity contributed in any way to the failure of the c/f function to consistently improve predictions made with the road model. The only strong relationship discovered indicated that for the five areas in which the c/f function failed to improve predictions, elk use of subunits with the heaviest available cover was greater than use predicted by the model. Subunits with relatively less cover were avoided.

Table 8.—Standardized mean square deviations, two cover/forage functions, and the single function-B road model on 11 study areas

Study area	Cover/forage function	
	Single c/f	No c/f
Skalkaho	0.81	0.84
Blue Mountain	1.62	1.68
Jim Creek	2.26	1.36
Beaver	4.19	3.04
Petty	1.00	.82
Bateman	.03	
Hyalite	1.26	1.27
Judith	.50	.49
Red Ives	.73	.82
Canyon	3.91	2.01
Newsome	.90	2.56
Average	1.56	1.36
Improved, 6 areas	.89	1.20
Not improved, 5 areas	2.37	1.54

Any major local disturbance requiring elk to seek the best available cover should have been detected during fieldwork. Observers, however, recorded no such disturbances. During the study a pole sale was activated in the Crooked subunit of the Skalkaho area; there were active timber sales adjacent to the Canyon, Petty, and Blue Mountain study areas; and the Newsome area was open to year-round hunting by the Nez Perce Indians. Nevertheless, only one of these areas is among the five for which the cover/forage function failed to improve the prediction. In those five areas, there was no consistent pattern of woodcutting, active timber sales, or other disturbance that might help to explain the elk selection for heavier cover.

DISCUSSION

Although there was no apparent relationship between elk selections for heavy cover and the time at which fieldwork was conducted, it would not be surprising if some undetected relationship did, in fact, exist. Fieldwork for this study was completed over a period of two summers, and it is possible that the variation observed simply demonstrates normal changes in seasonal habitat requirements. Skovlin (1982) and several others have described a strong seasonal gradient in habitat use by elk: through late June, open grasslands are the primary feeding areas and use of hiding cover is minimal. By August, warmer temperatures, drying forage, and insects produce a habitat shift to forest cover. Thus, even if the cover/forage function does describe an average habitat use pattern, it does not satisfactorily describe the temporal relationships.

CONCLUSIONS

Results of these field tests suggest that the road-density model is a very powerful tool for evaluating and manipulating elk habitat quality. The failure of the cover/forage curve to demonstrate equal power cannot be viewed as sufficient reason to reject the cover/forage concept. It would be somewhat surprising if a single simple function was able to account for changes in elk habitat requirements over the summer season. A more comprehensive model will be required to achieve adequate evaluation of cover and forage requirements that may change substantially between June and September.

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During the summers of 1980 and 1981, field tests of elk/timber coordination guidelines were conducted on 11 study areas in Montana and northern Idaho. Evaluations of elk habitat based on different combinations of cover/forage functions and road models were compared to pellet group distributions. Elk response to variations in habitat quality was primarily determined by road densities. Acceptable road models predict over 50 percent of the variation in habitat use by elk.

KEYWORDS: elk, timber, habitat quality, cover/forage, roads

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Provisions for Protecting and Enhancing Nontimber Resources in Northern Region Timber Sales

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RESEARCH SUMMARY

Forest Service timber sales frequently include provisions to protect or improve nontimber resources. But as economic conditions become increasingly restrictive, the costs incurred for nontimber purposes become more closely scrutinized. In order to evaluate the costs and effectiveness of these provisions, it is necessary to identify specific activities and management objectives being served. A questionnaire census of all timber-producing Ranger Districts in the Northern Region was designed to provide that information.

Results indicate that most timber sales incorporate provisions to mitigate harvest impacts (reduce, modify, or eliminate damages) or to enhance and improve resources other than timber. The nontimber resources examined in this study were cultural, fish, range, recreation, soil, visual, water, and wildlife. The nontimber resources most frequently involved are wildlife, soil, and water; least frequently involved, range and cultural resources.

In most cases special provisions are intended to mitigate damage to nontimber resources. In the case of range resources only, provisions for enhancement and mitigation were approximately equal in number.

The Design/Layout and Roads phases of a timber sale are modified most frequently to accommodate nontimber resources, the Loading/Hauling phase least frequently. All provisions for Erosion Control are mitigating, while most provisions in the Structures/Activities phase are enhancing.

The most common specific provisions for nontimber resources are the Location and Size of Cutting Units, together with Road Density and Location. Most specific activities serve more than one nontimber resource. Even some activities commonly associated with management of a specific, single nontimber resource are frequently applied to other resources. For example, Feathered Edge Cutting is closely associated with visual resource management, but is also used for wildlife purposes.

Provisions for Protecting and Enhancing Nontimber Resources in Northern Region Timber Sales

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INTRODUCTION

Forest Service, U.S. Department of Agriculture, timber sales are frequently developed to not only produce timber but also to meet other resource management objectives. A combination of high wood use, rising costs for management activities, and more stringent budgets calls for increased efficiency by managers. The challenge is to increase productivity—to do more for less. Both proponents and opponents of timber harvesting practices have urged greater attention to timber sale costs. But often information is insufficient to allow managers to analyze the costs and benefits.

Some costs are administrative—the result of staffing and maintaining a timber sale program. Other costs are the consequence of managing specific timber sales; the bulk of such costs presumably result from the occasion to sell and harvest timber. Some timber sale costs, however, accrue to nontimber objectives such as improving elk habitat or reducing visual impacts.

Cost-cutting efforts frequently amount to identifying and eliminating nonessential activities—"cutting out the fat." But for forestry organizations with multiple-use mandates, it is often difficult to distinguish between nonessential fat and essential lean. Some special interest groups oppose spending monies on nontimber resources; others clamor for more attention to such resources. Whether costs associated with nontimber resources are warranted ultimately rests on the value of the benefits produced or not foregone. How much do those nontimber activities cost and are they justified? A thoughtful answer to those questions goes beyond dollar estimates and includes a grasp of the role and scope of provisions for nontimber resources in timber sales. The provisions made for nontimber resources activities must be identified and the extent to which they are incorporated into timber sales must be understood. Furthermore, the purpose of those provisions must be determined since that can substantially affect the manner in which they are handled in an economic analysis. The analysis presented in this report identifies the provisions and describes the frequency with which they affect timber sales, both in the context of specific nontimber resources and the purpose of the provision.

METHODS

Data were collected by means of a mail questionnaire, cooperatively sponsored by the Intermountain Station and the Bureau of Business and Economics Research, University of Montana. A two-part questionnaire (available on request from the authors) was sent to all timber-producing Ranger Districts in the Northern Region of the Forest Service. All Ranger Districts responded; therefore, data and responses amount to population totals, devoid of sampling error. In total, data were obtained from 61 Ranger Districts on 13 National Forests. Most respondents were timber management assistants or District Rangers; the remainder came from various timber staff personnel. Respondents were instructed to restrict their answers to large-volume timber sales: sales of 500 M bd.ft. or more for northern Idaho and western Montana; 100 M bd.ft. for eastern Montana.

The object of the questionnaire was to assess provisions made in timber sales for nontimber purposes. Provisions identified were restricted to those that resulted in a significant modification of the timber sale relative to that where timber production was the only purpose. Respondents were asked to identify the nontimber resource intended to be affected by the provision, as well as the general intended purpose of the provision. The following nontimber resources were included:

Cultural (historical, archeological sites)	Soil
Fish	Visual
Range	Water
Recreation	Wildlife

Provisions were identified without regard as to why (requisiteness) or when (timing within a sale) they occurred. Some provisions identified are mandatory responses to policy requirements. Others are discretionary, involving voluntary choice. Clearly, this distinction can be judgmental. Provisions made in timber sales to meet Regional or Agency-wide standards are mandatory. Habitat protection efforts in compliance with the Endangered Species Act of 1973 might be judged mandatory. Other provisions are discretionary, as might include, for example, cutting stumps flush to the ground

to enhance visual amenities. Similarly, nontimber provisions in the original sale design were not distinguished from those subsequently added to the timber sale award. Provisions can be incorporated while planning the sale, through the Environmental Assessment process, or added while administering the timber sale contract.

Respondents identified only the resources of primary concern. Nevertheless, a given provision almost certainly affected other resources because management activities are so broad and the ecosystem so interconnected. Secondary effects, however, were not identified.

Respondents were asked to identify whether the general purpose of the nontimber provision was for mitigation or enhancement. We define mitigation as follows: to reduce, moderate, or prevent adverse effects on nontimber resources. Our definition of enhancement is: to improve the status of nontimber resources or products relative to presale conditions. Reducing soil erosion from skid trails would be considered mitigation; removing natural stream debris would be considered as enhancing the water resource. The questionnaire asked the purpose of the provision, not the actual outcome. Activities do not always accomplish the desired result, either mitigating or enhancing. Similarly, provisions to mitigate or enhance one nontimber resource may have the opposite, though unintended, effect on another resource.

Respondents were instructed to base replies on their best judgment. While detailed record searches were not requested, reference to records was not disallowed. The alternative of collecting data from a sample of timber sale records (which are readily available) was rejected. Companion research indicated that individual sale records only partially (and then sporadically) address our concerns. They do not provide a comprehensive, synthesized picture of the overall timber sale program. Responses to questions of primary resource affected, significant change, and general purpose of the provision are judgments that fundamentally depend on the perception of the timber manager.

Questionnaire responses were coded and entered into a data file suitable for computer analysis, using SPSS computer programs (Nie and others 1975). All Ranger Districts were assigned to geographical subregions within the Northern Region and data were aggregated by those strata. Figure 1 shows the boundaries of the subregions—northern Idaho, western Montana, and eastern Montana. The Continental Divide is the boundary between eastern and western Montana. Ranger Districts from the National Forests straddling the Divide were assigned to a subregion based on the location of the District Office.

Most questions required response in the form: percentage of sales modified. But because Districts vary in terms of number and size of sale, responses were evaluated under three weighting schemes—sale number, sale volume, and equal weighting. Except for some minor differences, results were virtually the same regardless of weighting system used. The largest differences did not change study results appreciably. Results displayed will be based on only the sale number weighting system. Therefore, study results consist of

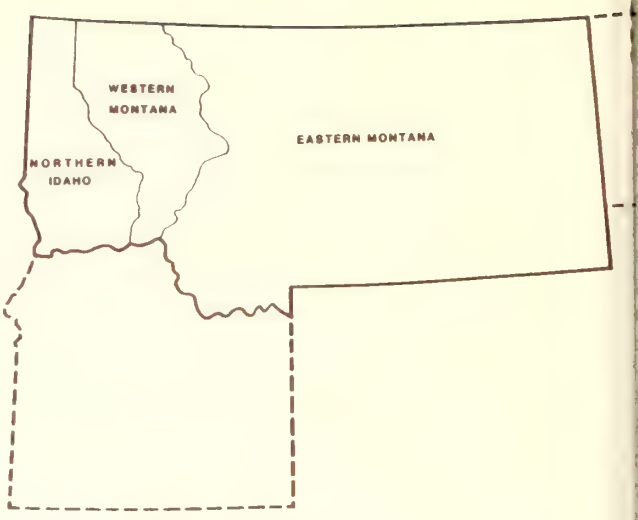


Figure 1.—Three subregions of study within Northern Region, Forest Service.

subregional aggregations of District-level responses weighted by the average annual number of large timb sales from 1977 through 1981.

RESULTS AND DISCUSSION

Most of the timber sales in the Northern Region include provisions pertaining to one or more of the eigh **nontimber resources**. The provisions appear to affect v tually all **timber sale phases**. A wide variety of **timber sale activities** are undertaken or modified to meet specific objectives. The following sections discuss thes three aspects of timber sales and describe geographica and other variations. Please note, although the followi results are increasingly specific, they are not nested. Results pertaining to sale activities cannot be aggregated to approximate results for sale phases; phase cannot be aggregated to resources. This is because pr visions for several nontimber resources can be made i single sale.

Nontimber Resources

The first task was to measure the frequency of prov sions in timber sales for nontimber resources and whether the provisions were intended to enhance or mitigate. The listing below shows that provisions are frequently made in timber sales for nontimber purpos in the Northern Region.

Nontimber resource	Percent sales with mitigation provisions	Percent sale with enhancem provisions
Cultural	23.2	10.9
Fish	44.1	25.0
Range	14.8	13.0
Recreation	35.0	27.1
Soil	55.8	15.9
Visual	59.2	34.5
Water	66.9	27.0
Wildlife	77.2	54.0

rovisions concerning wildlife were most prevalent—
ported in more than three-fourths of the timber sales.
easures affecting soil, water, and visual resources were
so common, each occurring on more than half of the
les in the Region. At the other extreme, cultural and
nge resources affect the fewest sales throughout the
egion. The frequencies shown indicate that most
mber sales in the Region contain provisions to meet
ntimber objectives. Provisions for mitigation greatly
tnumber those for enhancement. This is true for every
ntimber resource. The high frequency of provisions for
ch nontimber resource indicates that very few sales
ould be unaffected.

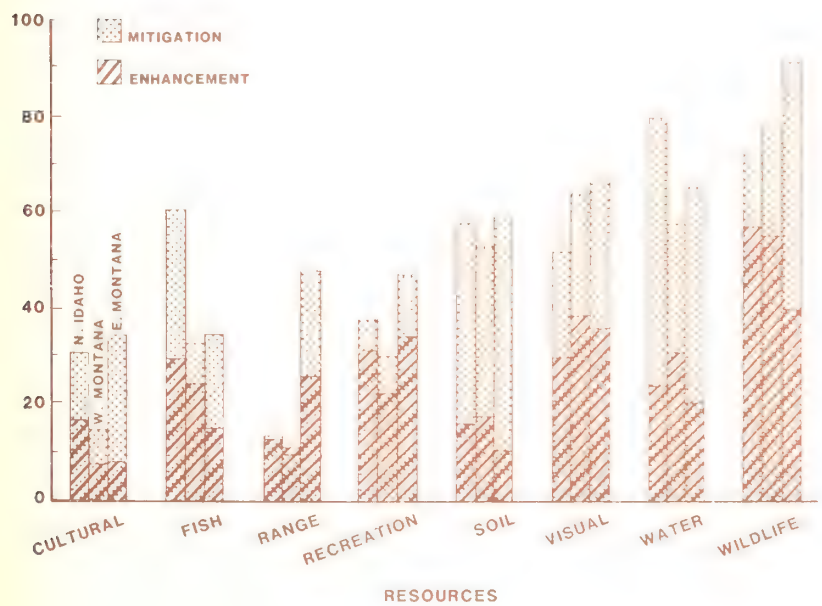
Figure 2 displays the same type of information, but
ecifically pertains to the three subregions. It shows
nsiderable differences among nontimber resources.
mber sale provisions for wildlife purposes prevail
roughout all subregions, occurring on more than three-
urths of the timber sales. This is to be expected
ecause timber-wildlife relationships are important
blic issues and the effect on wildlife habitat is always
professional concern. Similarly, the high frequency of
ovisions for water resources again is expected. Most
rest land is water-producing land and timber sales at
ast afford the potential to alter water quality or quan-
y along with timing of runoff.

At the other extreme, modifications for range and
ltural resources are least frequent. These resources are
ly occasionally proximate to timber. Furthermore,
ltural resources tend to be more concentrated (specific
storic sites, trails, etc.) and are not as likely to be af-
cted by timber harvest activities. Therefore, the low
vels of activities for these resources probably reflect a
ss common opportunity rather than a lack of inclina-
on to make timber sale provisions.

There is also considerable geographic variation and similarity in nontimber resources affected. The most striking differences pertain to fish, water, and range resources. Northern Idaho has numerous rivers and streams that are part of the Columbia River system. Timber sale provisions made for fish and water purposes probably reflect concern over the salmon and steelhead fisheries and the importance of water to their well-being. Similarly, range is frequently a concern in the more open forests of eastern Montana. There, forest grazing is much more common than in the more heavily forested areas of western Montana and northern Idaho.

Figure 2 also shows a consistent pattern of mitigation provisions greatly outnumbering enhancement provisions. Excepting range, this is true for every nontimber resource and every geographic area. The greatest difference is for water resources and soil resources, where mitigation provisions outnumber those for enhancement by roughly three to one. For example, although almost 60 percent of the sales in eastern Montana contain mitigation provisions for soils resources, only 10 percent contain enhancement provisions. Provisions are generally intended to protect existing water and to prevent soil erosion. And that gap may be understated, because some respondents indicated difficulty distinguishing between mitigation and enhancement provisions concerning soil resources; some identified enhancement efforts that really amounted to mitigation measures. There are few opportunities to improve soil and water conditions (excepting water quantity) because the natural, undisturbed state is the norm.

In contrast, enhancement and mitigation provisions are approximately equal for range and recreation resources. Perhaps managers believe that timber harvesting improves limited grazing opportunities,



gure 2.—Percentage of timber sales with ovisions to enhance or mitigate for non-nber resources, by resource and subregion.

especially in the more heavily forested areas. Similarly, roads increase access and probably enhance road-dependent recreation activities.

Range resources in eastern Montana and fish resources in northern Idaho show striking deviations from the Regional pattern. The percentage of timber sales modified for range purposes in eastern Montana is more than double that of any other subregion for enhancement, and is even higher for mitigation. In eastern Montana nearly all of the forest land is grazed, unlike other areas in the Northern Region. Similarly, the mitigation provision for fish resources in northern Idaho far exceeds that for other areas. In both cases, this probably reflects both the presence of relatively unique resources and the potential for unacceptable damage through timber sales.

Timber Sale Phases

An important part of understanding how timber sales meet nontimber objectives is to know where within a timber sale the nontimber resource provisions occur. That is, provisions for nontimber resources are decided when planning the sale and later during sale administration. When decisions are implemented, they result in activities that change the nature of the sale. This section focuses on the location of those activities. In order to make results compatible with conventional sale information, activities involved in a timber sale were stratified into eight broad categories or phases, generally following the timber sale appraisal form used by the Forest Service. A "design and layout" category was added to more completely portray the various aspects of a timber sale. The phases used were:

1. Sale Design/Layout
2. Roads
3. Felling/Limbing/Bucking
4. Yarding/Skidding/Decking
5. Loading/Hauling
6. Slash Disposal
7. Erosion Control
8. Sale Area Betterment
9. Structures/Activities

Decisions to provide for nontimber resources pertain to one of these categories.

The Sale Design/Layout phase was structured to consist of major, overall decisions such as location and size of cutting units and road density. The Roads phase pertains to road construction, reconstruction, and maintenance. The Loading/Hauling phase refers to movement and transport of logs from a log deck or landing to a processing facility. Sale Area Betterment commonly referred to as "K-V," use of Knutson-Vandenberg funds. Structures/Activities refers to construction and management of temporary structures such as gates or loading ramps as well as road closures or snag felling.

Table 1 provides a Region-wide perspective as to which timber sale phases and nontimber resources are most frequently subject to provisions. As noted previously, timber sale provisions for wildlife and then for soil and water resources clearly dominate other nontimber resources. Provisions made in Sale Design/Layout, along with the Roads are by far the most frequently modified sale phases. Finally, the frequency of provisions designed to mitigate effects totally overwhelm those for enhancement purposes.

Table 1.—Percentage of Northern Region timber sales modified for nontimber purposes, by sale phase, nontimber resource, and purpose

Timber sale phase	Nontimber resource							
	Cultural	Fish	Range	Recreation	Soil	Visual	Water	Wildlife
				Mitigation Purpose				
Sales Design/Layout	29.3	43.8	13.6	33.0	55.9	56.5	68.2	79.9
Road	18.3	49.5	15.0	35.3	65.4	49.3	63.1	57.9
Felling/Limbing/Bucking	6.7	33.8	6.2	15.6	11.2	23.2	48.2	22.9
Yarding/Skidding/Decking	13.6	48.3	7.5	21.4	54.5	41.2	57.5	33.7
Loading/Hauling	3.3	10.4	5.1	17.0	18.8	10.3	17.7	23.3
Slash Disposal	11.1	35.8	9.4	33.4	42.3	47.6	41.8	49.3
Erosion Control	1.8	43.5	8.1	15.0	65.2	19.2	67.4	19.3
Sale Area Betterment	4.7	29.4	18.7	20.5	26.3	23.7	28.7	62.2
Structures	2.6	9.3	11.7	9.8	10.3	9.7	12.3	56.3
				Enhancement Purpose				
Sale Design/Layout	0	5.1	1.1	5.2	6.9	13.4	2.4	6.5
Roads	7.3	22.2	8.3	25.7	22.3	22.8	29.9	28.0
Felling/Limbing/Bucking	4.6	14.0	3.6	6.6	5.4	14.9	18.3	15.1
Yarding/Skidding/Decking	6.6	17.5	5.7	7.8	16.5	24.3	23.3	22.3
Loading/Hauling	1.7	5.7	3.0	7.2	6.4	9.5	10.1	19.3
Slash Disposal	6.3	19.1	7.4	19.4	12.4	31.6	23.2	37.2
Erosion Control	0	0	0	0	0	0	0	0
Sale Area Betterment	2.0	18.4	9.2	4.9	27.0	9.0	27.9	18.8
Structures	7.7	25.0	11.6	29.0	19.9	38.6	32.9	55.9

Figure 3 shows how frequently each timber sale phase s modified and which nontimber resource is involved, nd compares subregions. For each resource, a series of istograms, one for each of the nine phases, shows the ercentage of timber sales modified to mitigate or nhance that particular resource.

Figure 3 provides for five visual comparisons:

1. A general nontimber resource comparison—an verall comparison of the frequency (height of bars) of nodifications from one panel (resource) to another.
2. A comparison of timber sale phases—comparing fre- uency of modification among sale phases within and etween resource panels.
3. Specific resource comparisons—comparing fre- uency of provision between sale phases, subregions, nd resource.
4. Enhancement versus mitigation comparisons— omparing segments of individual bars.
5. Subregional comparisons—comparing the heights of ne three bars for each sale phase.

Vith these comparisons in mind, the following are some f the principal findings.

The first comparison involves the overall heights of ars from one resource panel to another. The overall eights of the bars follow the same general pattern of rovisions for nontimber resources shown in table 1 and gure 2. That is, the overall histograms for wildlife and ater resources are the highest, and those for cultural nd range resources are the lowest.

The second comparison focuses on timber sale phases. igure 3 shows both a pattern of consistency and of onsiderable variation. Regardless of nontimber resource rea or subregion, the Sale Design/Layout and Roads hases clearly involved the most modification provi- ions. Conversely, Loading/Hauling had the least. These esults probably reflect the inherent opportunities to nodify activities for nontimber purposes. Loading/Haul- ng affords few opportunities, while Roads or Sale Design/Layout affords many. Beyond those generaliza- ons, several unique relationships exist between non- mber resources and sale phase. For example, Erosion ontrol provisions are very important for water esources, but inconsequential for cultural resources. imilarly, Yarding/Skidding/Decking is quite important or fish resources, but not for range resources except in astern Montana.

The wildlife resource panel of figure 3 illustrates infor- nation available to make resource-specific comparisons. or example, compare the wildlife panel to the cultural esource panel. Note that provisions for wildlife are con- istently included in all phases of the timber sale, and in nuch greater numbers, than for cultural resources. Also, ne Sale Design/Layout phase is the component most requently modified to provide for wildlife resources; the oads, Sale Area Betterment, and Structures/Activities hases are the next most frequent for sale modification.

n general, mitigation provisions greatly outnumber those for enhancement, with some important exceptions. Specifically, mitigation provisions only slightly outnumber those for enhancement for the Structures/Activities phase in northern Idaho, and enhancement provisions actually exceed those for mitigation in western and eastern Montana. Enhancement provisions also exceed mitigation for Loading/Hauling in western Montana. On the other hand, wildlife provisions made through Erosion Control are usually all mitigating. Finally, although the frequency of wildlife provisions in eastern Montana usually exceeds that for other areas, the relative importance of the various timber sale phases to wildlife provisions is very consistent across subregions.

Comparisons of mitigation provisions and enhancement provisions show two trends. First, Sale Design/Layout and Erosion Control provisions are almost exclusively intended to mitigate. In fact, no enhancement purposes were reported for Erosion Control. This seems particularly reasonable for Erosion Control because it is difficult to envision activities that could be considered enhancing. Second, in Structures/Activities, enhancement provisions almost always outnumber those for mitigation, the dominant exceptions being range resources in northern Idaho and western Montana together with soil and water resources in eastern Montana.

Finally, the information in figure 3 can also be compared geographically. The listing below shows the two most important categories (nontimber resource and sale phase) of modification for each geographic area, for mitigation (M) and enhancement (E):

Northern Idaho:	M	— Wildlife and Sale Design/Layout
		— Water and Erosion Control
	E	— Wildlife and Structures/Activities
		— Visual and Structures/Activities
Western Montana:	M	— Wildlife and Sale Design/Layout
		— Water and Sale Design/Layout
	E	— Wildlife and Structures/Activities
		— Wildlife and Slash Disposal
Eastern Montana:	M	— Wildlife and Sale Design/Layout
		— Wildlife and Roads
	E	— Wildlife and Structures/Activities
		— Recreation and Structures/Activities

The dominant nontimber resources are clearly wildlife and water. The dominant timber sale phases are Sale Design/Layout (for mitigation) and Structures/Activities (for enhancement).

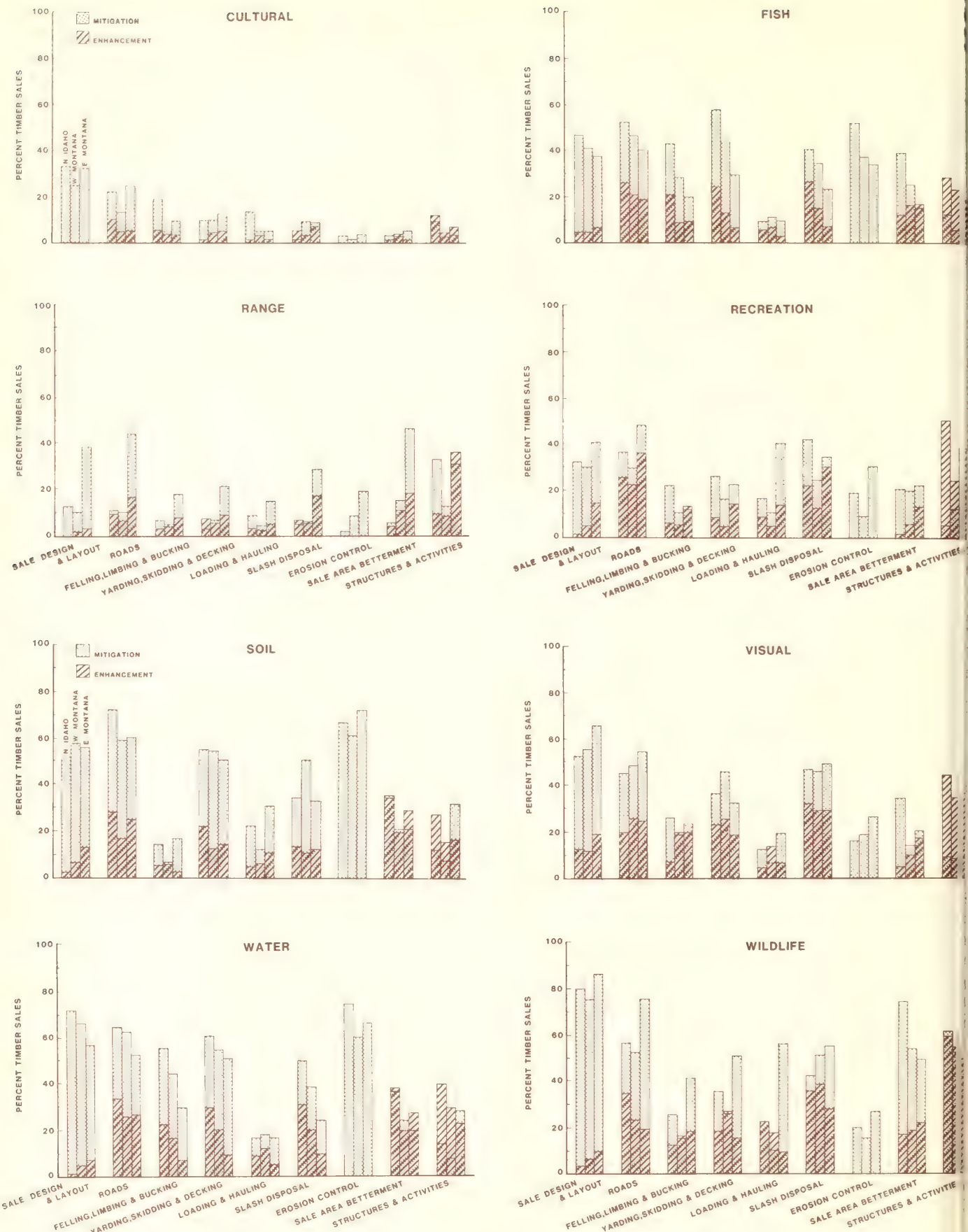


Figure 3.—Percentage of timber sales with provisions to enhance or mitigate for non-timber resources, by resource, timber sale phase, and subregion.

Timber Sale Activities

The final task was to identify timber sale activities sed to provide for nontimber resources and to de- ermine their relative frequency of use. Analysis of sale ctivity at this level of detail required that some sup- orting information be combined. First, the distinction etween provisions for mitigation versus those for nhancement purposes was dropped. It was not practical o obtain that level of detailed response concerning pecific activities with a mail questionnaire. Second, hereas preceding results were expressed in terms of ercentage of timber sales modified, the following esults are summarized by percentage of Ranger istricts in the Northern Region that use specific ac- vities. It was not practical to obtain the detailed infor- ation needed to determine the percentage of timber ales incorporating certain activities. We did, however, ontinue weighting District responses by number of mber sales, to be consistent with the other results eported earlier.

The respondents reported modifying more than four ozen specific activities to provide for nontimber esources. Only about half of these, however, were fre- uently and consistently used in all geographic areas. he listing below shows a rank ordering of the 10 most idely used practices, over all subregions and nontimber esources:

Timber sale activity	Rank
Location and size of cutting unit	1
Road—density and location	2
Road—seed, mulch, plant	3
Proportion of area harvested	3
Drainage—culverts, ditches, etc.	-
Road alinement and grade	6
Leave strips, streamside cover	7
Yarding/skidding direction and distance	-
Cross-ditch and water-bar skid trails	-
Cleaning trails and streams	8

he first two ranked activities were among the top five ctivities in more than three-fourths of the subregion- ontimber resource combinations.

Some readers may question the absence of silvicultural system" and "logging system" in the list bove and in the subsequent presentation. There are hree possible explanations for this situation. The first xplanation is that both items are, in fact, present, but epresented by several activities. For example, provi- ions for nontimber resources via modification in ilvicultural system may be reflected in Location and ize of Cutting Unit, Proportion of Area Harvested, eave Strips, and more. Second, logging systems are not ypically specified in a timber sale. But other specifica- ions may limit operator flexibility. For example, varia- ions in Road—Density and Location can substantially ffect use of helicopter, cable, or tractor-based systems. inally, choice of basic silvicultural and logging systems may be unrelated to nontimber resources. That is, clear- cut may be selected to promote even-aged management and helicopter logging to protect the residual timber stand. If these basic systems are then fine-tuned for nontimber purposes, the result may still fit within the definitional parameters of the original system.

Figure 4 shows how frequently all of the more com- monly used activities were cited. The list of specific ac- tivities includes only the 25 most frequently cited ac- tivities. Many more activities are actually used than are shown. Another 25 activities were also reported, but they were less common and were never among the top 5 activities for a given subregion or nontimber resource. For example, although more than half of the Ranger Districts in northern Idaho and western Montana have provided for wildlife through structures such as gabions and nest boxes, that activity is not within the top five wildlife-oriented activities for either subregion and is not listed in figure 4. Similarly, although firewood gathering is common, special firewood provisions were uncommon in timber sales.

The heavy shading in figure 4 indicates that specific activities relating to the Sale Design/Layout phase (first three activities) are the most frequently used. That phase includes decisions pertaining to area harvested and area and location of cutting units. Similarly, specific activities related to road density and location are also important. These activities all affect size of area treated, a major consideration in providing for nontimber resources. Activities pertaining to the Roads phase, such as installation of culverts or seeding roadways, are also very commonly used.

Results shown in figure 4 suggest a relationship be- tween pervasiveness of use and pervasiveness of effects. Activities that have widespread use tend to have widespread consequences. Activities having limited use have limited consequences. For example, provisions are made for all nontimber resources through the Location and Size of Cutting Units activity; and at the same time, the consequences of those provisions are far- reaching. On the other hand, Seeding and Planting for Wildlife is much less frequently used and its conse- quences are much more restricted.

Specific activities are rarely used exclusively for only one nontimber resource. This is shown in figure 4 by the presence of shading across nontimber resources for almost all activities. Usually a given activity can be used to provide for any of several nontimber resources. For example, except for range resources, the impacts of Road Density and Location are commonly considered for all other nontimber resources. Even "Feathered Edge" cutting, which is generally considered to be a visual management technique, is frequently used to manage wildlife in northern Idaho. But figure 4 includes just the top five activities for each nontimber resource and subregion combination. If all activities were included, there would probably be a greater occurrence of single- resource activities.

Figure 4.—Percentage of Ranger Districts using specific timber sale activities as provisions for nontimber resources, by resource and subregion.

MANAGEMENT IMPLICATIONS

The previous sections have highlighted several important aspects of timber sale provisions for nontimber purposes. Various issues were addressed. Which nontimber resources are most commonly the target of timber sale provisions? Was the provision intended to mitigate or enhance those resources? Which phase(s) within the timber sale do the provisions involve? What forms—specific activities—do timber sale provisions take? Variations in these issues resulting from geographical considerations were also discussed. The purpose was to provide a preliminary basis on which to deal with efficiency and cost effectiveness in timber sale design.

It is important to recognize the legitimate distinction between timber sale provisions made for mitigation and enhancement purposes and to treat them properly in any economic analysis. Costs incurred for mitigation activities are rightfully assigned to the timber resource. Presumably, without these activities, nontimber resource production would be lowered; the value of these reduced levels would be assessed in economic analysis of the timber sale. Whether or not the mitigation costs incurred (to prevent loss) are less than, equal to, or greater than the value of the loss is a separate question. Costs incurred and values gained from resource enhancement could be analyzed separately if desired. These activities and their costs could be conceived as independent production processes and evaluated accordingly.

Whether or not costs borne for nontimber purposes are warranted ultimately rests on the magnitude of the benefits received or not foregone. Our results do not indicate magnitude of costs and should not be so interpreted. We have measured the frequency of timber sale modifications only. Frequently applied modifications may, for example, be relatively inexpensive or have little impact compared to modifications that are infrequently applied, or vice versa. We simply do not know.

Even though estimation of dollar costs was beyond the scope of research reported here, results disclose two factors that profoundly influence costs. The most common provisions to modify timber sales are related to sale size. Such provisions directly affect harvesting costs and product recovery. The second most common provisions to modify a sale are related to roads. Because roads are one of the most expensive aspects of forest management, there is a high likelihood of substantial cost implications. Roads widely spaced to benefit wildlife might substantially reduce road construction costs, but increase yarding costs.

Results of this study indicate that most timber sales are affected by provisions for nontimber resources. Results also indicate where these provisions are made and for what purpose. The next step would be to estimate these costs and compare them to output. Measuring costs is difficult. But associating costs with specific nontimber resources will be even more difficult because, as shown, many provisions serve several target resources and probably affect others as well.

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Timber sale provisions to mitigate impacts on or enhance nontimber resources are discussed for the Northern Region, Forest Service. Data were obtained by questionnaire. Wildlife, soil, and water resources were the most frequent concerns. Special provisions were usually incorporated into design and layout of the sale and roads, and typically protect, not enhance, nontimber resources.

KEYWORDS: timber sales, nontimber resources, costs, economic analysis

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Tree Diameter Measurements At English and Metric Standard Heights: A Comparison

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RESEARCH SUMMARY

The impact of measuring trees at 1.3 m versus 1.37 m heights above ground line was analyzed. The results indicate that the difference in diameter measurement taken at the two points averages around 1 percent. An equation for converting from English diameter at breast height to the metric equivalent of 1.3 m is presented.

Tree Diameter Measurements At English and Metric Standard Heights: A Comparison

Dwane D. Van Hooser
David C. Chojnacky

INTRODUCTION

On December 23, 1975, President Ford signed into law the Metric Conversion Act. The act calls for voluntary conversion; however, foresters who attempt to comply may be faced with some rather difficult decisions on how to conduct their traditional field inventories and data analyses.

The Nationwide Forest Survey is a good example. At present, trees are measured to specified merchantability standards. Should these standards be maintained and "soft" conversion to metrics be accomplished through application of various factors or should the standards be changed to conform to even centimeter/meter classes? Similarly, should volume models based on English units be converted or should new metric models be developed?

Fundamental to many of the questions relating to metric conversion is: Where should diameter at breast height (d.b.h.) be measured? International users of the metric system commonly measure d.b.h. at 1.3 m. Both Australia and Canada, for example, have accepted this point on the stem as their measurement standard. Other countries, such as the United States, have traditionally measured d.b.h. at 4.5 ft. In metric this converts to 1.37 m, 7.2 cm higher on the bole than the metric standard.

In the United States, the Society of American Foresters, working with the American National Metric Council, is proposing that d.b.h. be measured at 1.3 m above ground line (Folliott and others 1982).

Some ongoing inventories are taking measurements in metric units, including diameter at 1.37 m, and then through conversion computing standard reporting units (Oswald 1979). Most, however, are taking measurements in the usual manner and then showing metric equivalents in the reports. Procedures have been developed to convert English diameter measurements to the metric to produce volume estimates in cubic meters. Bruce (1979), for example, gives the following diameter conversion for West Coast Douglas-fir:

$$\text{metric d.b.h.} = 1.00513 \text{ English d.b.h.}$$

Berry (1980) developed another conversion for white spruce:

$$\text{metric d.b.h.} = -0.049 + 1.01 \text{ English d.b.h.}$$

Bruce also cites a New Zealand study that suggests applying the conversion factor 1.0075 to the coefficient for d.b.h. in volume equations based on English measurement.

Meyers and Edminster (1974) present a method for converting from English to metric units volume equations of the form

$$\text{Volume} = a + bD^2H.$$

But there is no mention about the effect of diameter measurement taken by English versus metric standards.

Demaerschalk (1972) also gives procedures for conversion of taper and volume equations from English to metric units. Again, there is no comment about the effects from place of diameter measurement.

In the Rocky Mountains, the English volume equations are in numerous model forms not amenable to simple metric conversion. The most practical approach is to continue taking field measurements in English units, use existing English volume equations, and convert results of the equations to metric units—a soft conversion method. An initial phase in exploring this approach was to determine whether or not there was a significant difference in volume prediction from English equations when using d.b.h. measured at 1.3 m instead of 1.37 m for Rocky Mountain species. If the difference was significant, a correction factor for adjusting 1.37 m d.b.h. to 1.30 m d.b.h. for use in soft conversion of English volume to metric volume had to be developed.

METHODS

Fieldwork.—Data for this study came from a cooperative timber inventory conducted by the Forest Service and the State of Colorado in Grand County, Colorado. The inventory design systematically covered the county on a 5 000-m grid. Plots consisted of ten 40-basal area factor sampling points. Diameter of all sample trees was measured at 1.3 and 1.37 m above the ground line. Additional data were collected, but only diameter and height measurements were used for this study. Six species were represented: Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), Engelmann spruce (*Picea engelmannii* Parry), lodgepole pine (*Pinus contorta*

Dougl.), subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), aspen (*Populus tremuloides* Michx.), and narrowleaf cottonwood (*Populus angustifolia* James).

Each species was considered separately for comparison of English with metric diameter measurements. Diameter measurements taken by the two standards differed by only a few tenths of an inch. Because volume prediction is the primary use of the diameter measurement, the diameter data were analyzed in terms of effect on volume prediction. A relative percent difference statistic was derived to make comparisons:

$$VDIFF = \frac{MV-EV}{EV} \times 100$$

where:

VDIFF = Percent volume difference between volumes computed with metric and English diameters.

MV = Volume computed with diameter measured at 1.3 m.

EV = Volume computed with diameter measured at 1.37 m.

Gross cubic-foot volume equations (to a 4-inch top) were used for cottonwood (Kemp 1958), Engelmann spruce (Myers and Edminster 1972), subalpine fir (Hatch 1975), Douglas-fir (Hatch 1975), aspen (Edminster and others 1981), and lodgepole pine (Myers 1972). All of these equations were developed using English standards with d.b.h. measured at 4.5 ft (1.37 m).

Statistics were analyzed by constructing 95 percent confidence limits on the volume difference statistic (VDIFF) sorted into groups by species and 2-inch diameter classes using both Student's t-test and the ch square test. The chi-square confidence limits were deriv ed using the pivotal quantity method (Mood and others 1974).

Student's t-test is commonly used in making paired comparisons, but Freese (1960) points out the chi-squar test is more appropriate in most forestry applications. The chi-square test considers both bias and precision when making a paired comparison, while Student's t-te considers only bias. Both tests require normally distributed data. Figure 1 illustrates that this is a reasonable assumption for subalpine fir. The other species data had similar distributions. Table 1 lists the data with both Student's t-test and chi-square confidence limits. If a confidence limit does not include zer there is a statistically significant difference between English and metric points of measurement. The confidence limits do not include zero for the most part. Those that do include zero are for a small sample size c for small trees that were not compatible with the volun percentage (VDIFF) transformation. Thus, these tests i dicate that statistically the diameters taken at 1.3 m and 1.37 m are different, which is not unexpected. The question then becomes what impact will the diameters taken at the different measurement points have on volume?

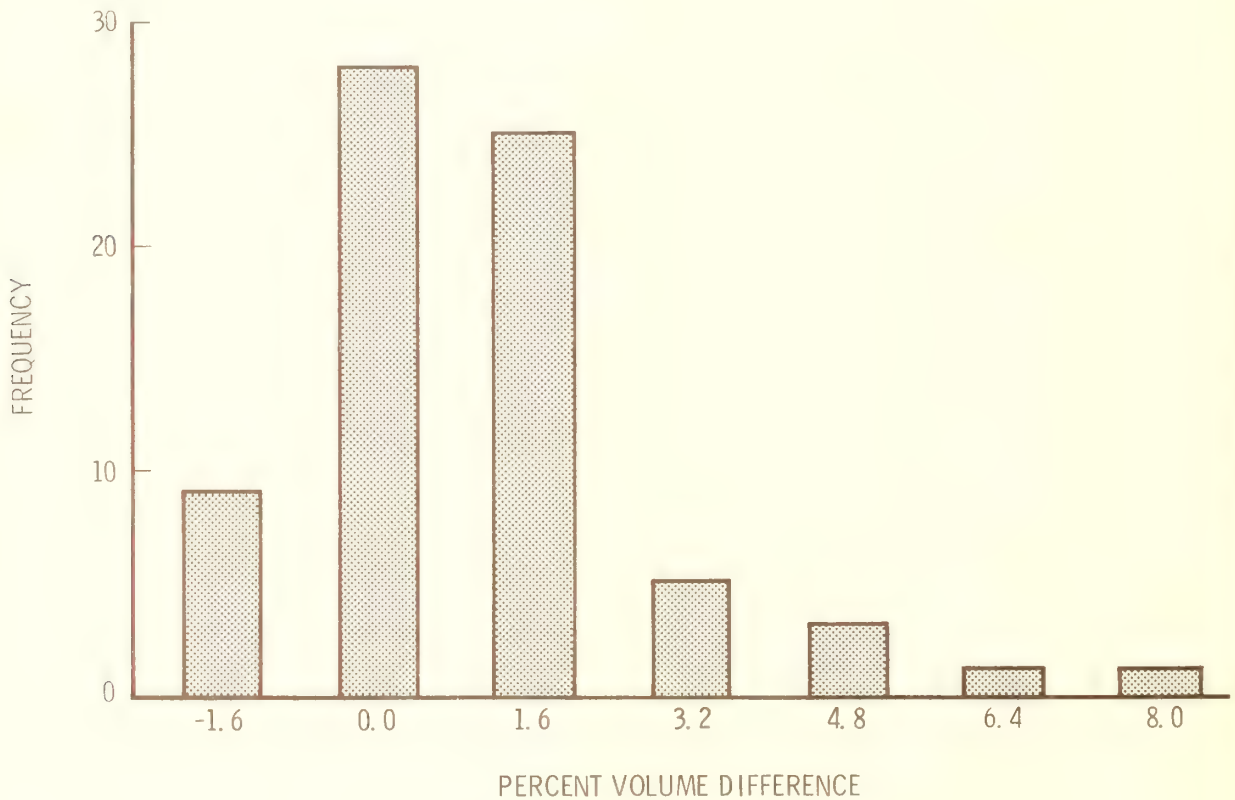

Figure 1.—Volume differences (VDIFF) for subalpine fir computed with metric and English diameters.

Table 1—Comparison of volumes (expressed as percentages) computed from diameters measured at 1.3 m (metric diameter) and 1.37 m (English diameter). Confidence limits (CL) are at the 95 percent level.

Diameter class	Number of trees	Mean diameter difference	Mean volume difference[1]	Median volume difference	Maximum volume difference	Minimum volume difference	Lower CL t-test	Upper CL t-test	Lower CL chi-square	Upper CL chi-square
				Eucalyptus						
5-6.9	34	.02	7	1.5	4.4	6.8	.18	1.59	58	.90*
7-8.9	33	.06	1.5	1.0	7.1	3.1	[illegible]	2.37*	1.39	1.74*
9-10.9	29	.01	.3	7	6.6	11.0	.69	1.35	.18	.57*
11-12.9	21	.10	1.5	6	8.8	.7	.37	2.56*	1.27	1.83*
13-14.9	12	.07	1.6	5	6.3	1.0	.36	2.27	.70	1.55*
15-16.9	8	.16	1.9	9	4.6	.0	.31	3.42*	1.44	3.08*
17-18.9	3	.12	1.2	8	2.0	.8	.63	3.02	.70	4.32*
19-20.9	1	.24	2.2	2.2	2.2	2.2			.25	7.79*
21-22.9	1	-.12	1.0	1.0	1.0	1.0			1.89	1.62
23-24.9	1	.16	1.2	1.2	1.2	1.2			.14	4.24*
Total	143	.05	1.6				.63	1.42*	.99	1.07*
				Lodgepole pir						
5-6.9	153	.03	1.4	1.0	16.6	24	[illegible]	2.09*	1.32	1.44*
7-8.9	219	.03	9	1.0	12.5	17	[illegible]	1.25*	.83	.89*
9-10.9	254	.05	1.1	.8	14.5	5.4	[illegible]	1.34*	1.05	1.09*
11-12.9	155	.07	1.1	.7	9.7	6.0	[illegible]	1.46*	1.06	1.13*
13-14.9	118	.07	1.0	.5	9.1	6.4	.56	1.37*	.93	[illegible]
15-16.9	44	.06	.7	.7	[illegible]	6.4	[illegible]	1.37*	.66	.87*
17-18.9	19	.02	.8	.4	7.4	1.7	.12	1.69	.63	1.08*
19-20.9	6	.07	.7	.6	1.5	[illegible]	.12	1.52	1.49	1.44*
Total	968	.05	1.1	[illegible]	[illegible]	[illegible]	[illegible]	1.22*	1.03	1.05*
				Englemann spru						
5-6.9	23	.05	2.0	[illegible]	22.2	35	2.35	6.45	1.37	3.26*
7-8.9	32	.05	1.1	1.1	9.4	3.9	.46	2.68*	1.40	1.85*
9-10.9	26	.08	1.4	1.3	5.8	3.3	[illegible]	1.96*	1.33	[illegible]
11-12.9	44	.08	1.4	1.3	5.8	3.3	.87	1.96*	1.33	1.54*
13-14.9	29	.11	1.6	1.1	7.8	.6	.87	2.26*	1.43	1.78*
15-16.9	42	.08	1.0	[illegible]	[illegible]	3.5	.49	1.56*	.95	1.15*
17-18.9	24	.11	1.1	1.4	[illegible]	[illegible]	.69	[illegible]	1.05	1.33*
19-20.9	19	.14	1.2	1.0	3.2	0	.75	1.58*	1.05	1.38*
21-22.9	5	.11	.9	.6	2.6	0.3	.48	2.28	.57	2.22*
23-24.9	3	.25	1.8	[illegible]	[illegible]	.8	.45	4.11	1.10	6.44*
25-26.9	5	.28	[illegible]	1.9	3.1	1.3	1.16	2.84*	1.49	4.07*
27-28.9	2	.18	1.1	1.1	[illegible]	.5	7.12	9.42	.47	5.38*
>29	4	.13	.6	.6	2.0	0	.74	2.34	.46	2.48*
Total	260	.09	1.4	[illegible]	[illegible]	[illegible]	[illegible]	1.86*	1.40	1.46*
				Cottonwood						
5-6.9	3	-.04	1.4	2.4	4.2	5.9	14.2	11.43	3.00	8.96
7-8.9	3	.05	1.6	[illegible]	[illegible]	[illegible]	-5.38	8.64	.58	8.22*
9-10.9	2	.04	.9	.9	.8	.9	-1.76	.01	1.32	1.94
11-12.9	12	.05	.8	1.4	5.9	4.0	.85	2.47	.50	1.52*
13-14.9	8	.22	3.3	2.5	8.9	-2.3	.08	6.59	2.44	5.61*
15-16.9	3	.10	1.4	1.6	[illegible]	[illegible]	1.88	4.69	.75	5.55*
17-18.9	5	.10	1.1	1.3	3.5	.5	.94	3.17	.66	2.94*
19-20.9	7	.08	.8	1.3	2.1	1.2	-.31	1.97	.57	1.65*
21-22.9	1	.08	.7	.7	7	.7			.09	2.65*
23-24.9	1	.04	.3	.3	3	3			.04	1.22*
25-26.9	1	-.28	-2.2	-2.2	2.2	2.2			4.06	3.47
Total	46	.08	1.1				.24	1.91*	.97	1.23*

Table 1—(con.)

Diameter class	Number of trees	Mean diameter difference	Mean volume difference[1]	Median volume difference	Maximum volume difference	Minimum volume difference	Lower CL t-test	Upper CL t-test	Lower CL chi-square	Upper C chi-squa
					Aspen					
5-6.9	104	.04	2.5	1.5	49.5	-29	.74	4.34*	2.38	2.74*
7-8.9	134	.02	.7	0	14.8	-9.8	.03	1.33*	.63	.75*
9-10.9	65	.05	1.1	.9	19.5	-25	-.24	2.41	.95	1.28*
11-12.9	31	.07	1.1	.7	11.2	-2.7	.11	2.14*	.97	1.37*
13-14.9	12	.11	1.4	1.3	3.9	-2.4	.27	2.46*	1.12	1.95*
15-16.9	2	.02	.2	.2	.5	0	-2.65	3.11	.06	1.26*
17-18.9	1	-.28	-3.0	-3.0	-3.0	-3.0	.	.	-5.57	4.76
Total	349	.04	1.4	.	.	.	.72	2.00*	1.33	1.40*
					Douglas-fir					
5-6.9	4	.09	3.4	2.6	11.3	-2.8	-6.01	12.78	1.59	12.26*
7-8.9	2	0	.1	.1	3.0	-2.8	-37.04	37.56	-1.40	9.57
9-10.9	1	0	0	0	0	0	.	.	0	0
11-12.9	1	-.20	-3.1	-3.1	-3.1	-3.1	.	.	-5.77	4.93
13-14.9	2	.06	.8	.8	1.0	.5	-2.33	3.86	.35	3.34*
15-16.9	3	.10	1.1	.4	3.0	0	-2.83	5.09	.49	5.16*
17-18.9	2	.33	3.3	3.3	4.2	2.4	-7.63	14.23	1.56	14.25*
19-20.9	1	0	0	0	0	0	.	.	0	0
23-24.9	1	.47	3.6	3.6	3.6	3.6	.	.	.42	12.85*
Total	17	.10	1.5	.	.	.	-.23	3.26	1.20	2.14*

*The 95 percent confidence limit does not include zero. This means there is a statistically significant difference between volumes computed with Engli and metric diameter measurements.

[1]Mean volume difference $= \sum_{i=1}^{n} \frac{MV_i - EV_i}{EV_i} \times 100/n$ where: MV_i = volume in cubic feet computed with metric diameter.

EV_i = volume in cubic feet computed with English diameter.

The average difference between metric and English diameters was mostly less than one-tenth inch, which corresponds to a little more than 1 percent bias. This positive bias is the expected result of using diameters measured at 1.3 m in volume equations developed for 1.37 m diameter measurements. The confidence limits indicate that the bias is most likely a population characteristic of about 1 to 2 percent.

Because most volume equations probably predict within 10 to 20 percent of the true value, a correction of 1 percent bias between metric and English measurements provides only a minor improvement in precision. Table 2 shows that a single correction for all species measured in Grand County, Colorado, is sufficient. The full and reduced model concept from Graybill (1976) was used to make this determination. The full

Table 2.—Results of testing six individual equations against the combined equation for predicting English d.b.h. from metric measurements

Source of variation	Degrees of freedom	Sum of squares	Mean square	F—value
Total	n = 1,783	221,188.6943		
Combined equation	p = 12	221,157.3758		
Individual equations	p - q = 2	221,157.2334		
Combined minus Individual	q = 10	.1424	0.01424	0.8054 ns[1]
Error variance	n - p = 1,771	31.3185	.01768	

[1]The .05 significance level is 1.83 for an F-value with 10 and 1,771 degrees of freedom. Hence, the hypothesis is accepted and each of the individual equations can be represented equally well by the combined equation.

model includes all species separately and the reduced model groups all species into one equation. The F-value is very small, indicating one correction equation is sufficient.

The equation is:

Metric d.b.h. = -0.0128 + 1.0065 English d.b.h.

Sample size = 1,783 trees

A plot of the actual minus predicted values (residuals) is shown in figure 2.

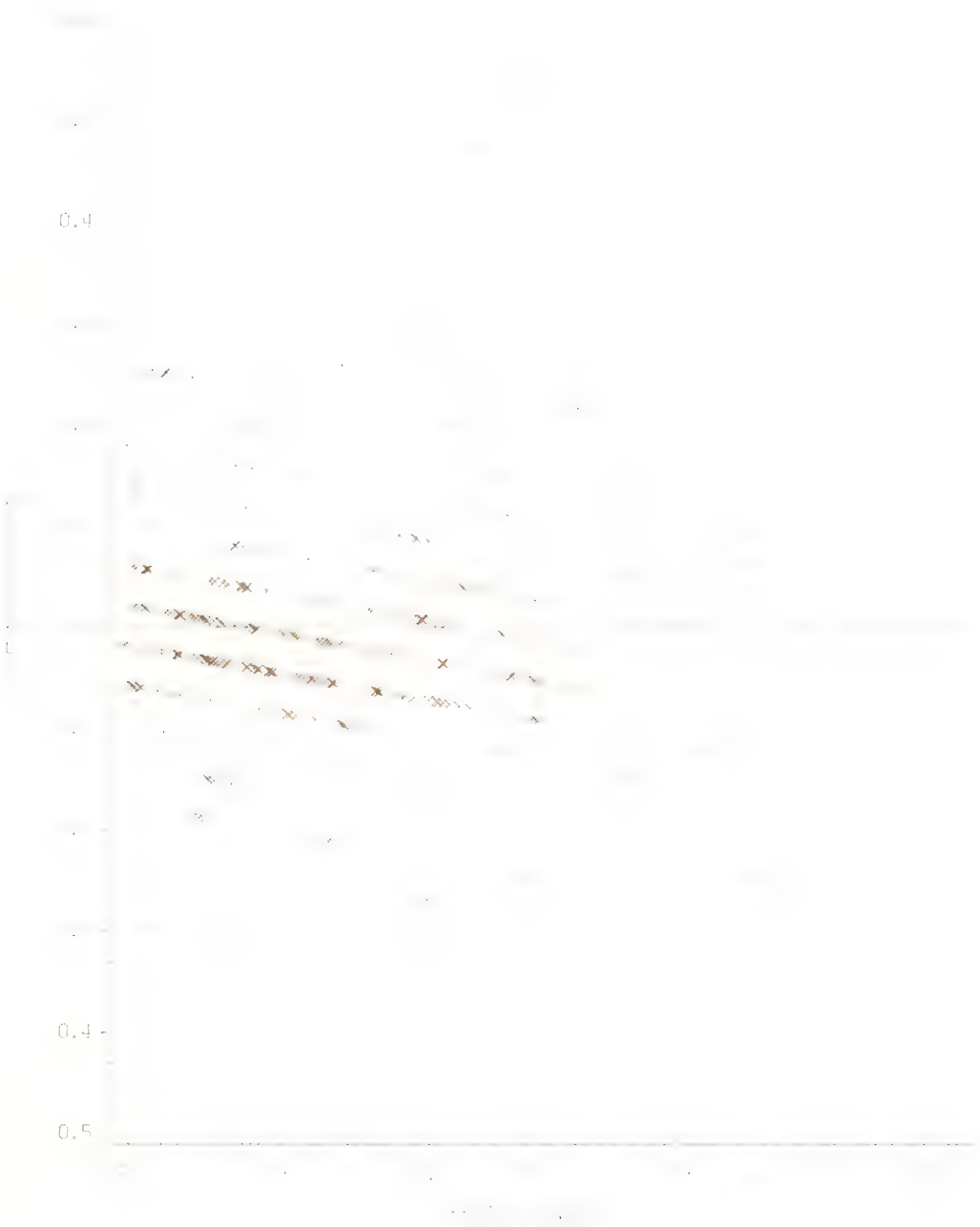

Figure 2.—A random subsample of residuals and predicted values for the model: metric d.b.h. = -0.0128 + 1.0065 English d.b.h.

DISCUSSION

The results of this study, while based on a rather restricted geographical sample, indicate that there is a small but statistically significant difference between diameter measurements taken at 1.37 m and those taken at 1.3 m. The correction factors developed for Grand County compare favorably with those presented by Bruce (1979) and Berry (1980). For example, assuming a 10.0-inch measurement taken at 4.5 ft (1.37 m), the formula developed by Bruce would yield a diameter of 10.05 at 1.3 m; Berry's correction would yield a diameter of 10.05 at 1.3 m, and the correction presented here would also yield 10.05. The implication is the equation presented here developed from Rocky Mountain species is functionally the same as those developed for naturally grown West Coast species and plantation-grown white spruce in Canada.

Since most volume equations are a function of diameter squared, it would follow that the next concern would be the impact of these diameter differences on volume. The relative difference (dash line in fig. 3) in volume estimates using diameter measured at 4.5 ft as opposed to 1.3 m is small. Generally, the largest relative difference is in the 6-inch-diameter class and continues to decline as diameter increases.

When this study was conducted, the trend in forest measurements in the United States was very much toward metric. Subsequent National policy, however, has deemphasized the adoption of the metric standard. Therefore, hard conversions to metric, in the near future at least, will probably not be required. Soft conversions, however, will still be required for comparative purposes in the international arena.

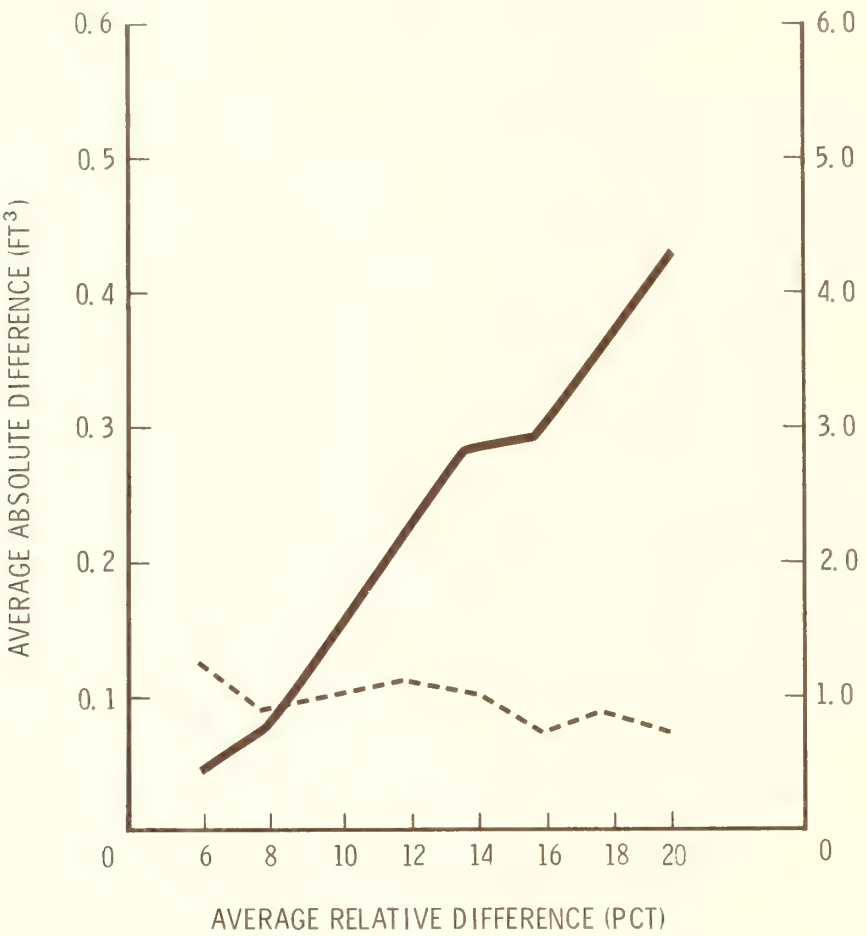

Figure 3.—Comparison of absolute (solid line) vs. relative (dashed line) differences in volume prediction using diameter measured at 4.5 ft vs. 1.3 m for lodgepole pine in Grand County, Colo.

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Van Hooser, Dwane D; Chojnacky, David C. Tree diameter measurements at English and metric standard heights: a comparison. Research Paper INT-327. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1984. 7 p.

Compares the difference between diameter and volume determination based on the English (4.5 ft, 1.37 m) versus the metric (1.3 m) diameter at breast height standard. Appropriate statistics are included and an equation for converting English to metric is presented.

KEYWORDS: volume, measurement, metric, diameter, diameter breast height

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Crop-Tree Thinning a 50-Year-Old Western Larch Stand: 25-Year Results

Dennis M. Cole

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RESEARCH SUMMARY

This paper describes study results after 25 years of crop-tree thinning in a western larch (*Larix occidentalis* Nutt.) pole stand in western Montana. Five ½-acre plots were established in the Petty Creek drainage, Lolo National Forest, at an elevation of 4,200 feet above sea level. Western larch site index of the study area was 52 feet at 50 years. The stand was 50 years old when the study began in 1949. Two plots were thinned by the D+4 Rule, two by the Crown Rule, and one was left unthinned as a control. After 25 years, periodic diameter, basal area, and volume growth of crop trees on thinned plots were significantly greater ($P = 0.05$) than designated crop trees in the unthinned plot, but differences are declining. Although statistically greater, the increase in crop-tree diameters—the major objective of the thinning—was not practically important, amounting to less than a 1 percent increase over crop trees in the unthinned control. Also, the crop-tree thinnings resulted in markedly lower basal areas and volumes of the total stand. From the results of this study, crop-tree thinnings by the D+4 or Crown Rules are not recommended for overstocked 50-year-old western larch stands, unless other resources benefit enough to offset the disappointing crop-tree growth response of the thinned stand. Instead, low thinning is recommended, preferably when the stand is younger.

Crop-Tree Thinning a 50-Year-Old Western Larch Stand: 25-Year Results

Dennis M. Cole

INTRODUCTION

Nearly 1 million acres of immature western larch (*Larix occidentalis* Nutt.) stands in the Northern Rocky Mountains are overstocked; neither adequate volume nor quality of usable wood is being produced. In many cases, this overstocking limits other forest resources, such as wildlife habitat and water (Schmidt and others 1976). Thinning can reduce some of these negative effects, but the question is just how to thin a specific stand. A lot depends on individual tree size objectives and the levels of other resource values, such as water yields and wildlife browse and cover, that the manager desires. But once objectives have been formulated, the manager still needs to know the consequences of the different methods, levels, and intervals of thinning in immature larch stands of various sites, ages, and densities.

Some information on thinning effects in western larch is available from earlier experiments. Schmidt and others (1976) reported on growth of individual trees in managed and unmanaged seedling-sapling stands (age 5-20 years). When projected to rotation, average crop-tree (trees selected to produce the crop on the basis of spacing, health, and size) diameters and hence merchantable crop-tree volumes of thinned stands were 60 to 65 percent higher than the same number of comparable trees in moderately overstocked stands left unthinned. But they emphasized that thinning only concentrates the wood on fewer but larger stems; total cubic volume yields are not increased, except in seriously stagnated stands. They recommended low thinning at an age of 10 to 15 years with trees selected to provide the desired spacing and species composition. Seidel (1977) reported 10-year results from a precommercial low thinning in a 33-year-old western larch stand in eastern Oregon. This stand, initially stocked with an average of 1,265 trees per acre and an average basal area of 134 ft^2, was thinned to basal areas of about 25, 50, 70, 95, and 110 ft^2. Trees in the lower density plots grew faster in diameter, but not in height, than trees in the high density plots. Nevertheless, increment per acre of both basal area and total cubic volume was greater at each higher level of basal area left after thinning. Seidel (1980) also found similar relative effects after 10 years in a test of four levels of low thinning versus four levels of thinning from above—in a 55-year-old western larch stand in which thinning from below was clearly the superior method. Illingworth (1964) and Thompson (1969) reported 5- and 10-year results of crop-tree thinnings in a western larch pole stand in British Columbia. Removal of trees within 8, 12, and 16 feet of crop trees was compared to crop trees left in an unthinned situation. Diameter increments of crop trees responded proportionately to the amount of extra growing space provided, but both basal area and volume growth per acre decreased with thinning intensity.

These studies confirm commonly understood principles of growth redistribution in thinned stands. But, because they vary in geographic location, thinning methods, and site, age, and density of the stands, it is risky to generalize from them or compare the data quantitatively. For example, one should not, with the above-noted differences, use periodic growth values from thinning studies of older pole stands to interpret future performance at the same age of stands thinned when they were much younger. Only followup investigation of longer term stand development of the various thinning studies can provide the data needed to reliably estimate future growth and yield effects. This paper presents growth results after 25 years of an earlier reported study (Roe and Schmidt 1965) of two methods of crop-tree thinning commonly used in western Montana at the time this study began.

STUDY DESCRIPTION

Study Area

Five 1/2-acre plots were established in the West Fork Petty Creek drainage, Lolo National Forest, Mont. The study site is about 4,200 feet above sea level. The plots are on north to northeast aspects, and range in slope from 25 to 55 percent. Average western larch site index of the site is 52 feet at 50 years, according to the most recent site curves for western larch (Schmidt and others 1976). In 1949, the stand was about 50 years old and was composed principally of western larch, with a minor component of lodgepole pine (*Pinus contorta* var. *latifolia*), Douglas-fir (*Pseudotsuga menziesii* var. *glauca*), and ponderosa pine (*Pinus ponderosa* var. *ponderosa*). Habitat types in the study area are *Pseudotsuga menziesii/Linnaea borealis* (PSME/LIBO) and *Pseudotsuga menziesii/Vaccinium globulare* (PSME/VAGL), both of low-to-moderate site quality for western larch.

Study Design

On each plot, between 160 and 200 crop trees per acre were chosen. Preference was given to western larch, ponderosa pine, Douglas-fir, and lodgepole pine, in that order. As far as possible, only dominant and codominant trees of good form and vigor were chosen. Because of marking preference and the predominance of western larch in the stand, the resultant crop trees were mostly western larch. Thinning treatments were completed in October 1949, as follows:

1. On plots 1 and 2, the "D+4" rule of thumb was applied to individual crop trees. All trees were killed around each crop tree for a radius in feet equal to the diameter of the crop tree in inches plus 4.
2. On plots 3 and 4, all trees were killed for a radius of 3 to 6 feet from the crown edge on at least three sides of each crop tree.
3. Plot 5 was left unthinned, but similar crop trees were marked for later comparison.

Competition trees in thinned plots were removed, according to the above thinning rules, in October 1949 by cutting, axe girdling, and poisoning. Trees smaller than 5 inches d.b.h. were cut with axes; those 5 inches and larger were girdled on plots 2 and 4, and poisoned on plots 1 and 3. Thus, each thinned plot had two treatment factors as follows:

Plot 1 — D+4 Rule, poisoning method
Plot 2 — D+4 Rule, axe method
Plot 3 — Crown Rule, poisoning method
Plot 4 — Crown Rule, axe method

Because there was no replication of the individual thinning rule/thinning method combinations, the differences among thinned plots could not be statistically tested. However, statistical tests were made of growth differences between thinned and unthinned plots, as discussed later.

Measurements

Before thinning, all trees greater than 0.5 inches d.b.h. were tallied by 1-inch diameter classes on all plots. After thinning in 1949, crop trees in all plots were recorded by species, measured for d.b.h. to the nearest 0.1 inch and for height to the nearest foot. Other noncrop trees left in the plots after thinning were tallied by 1-inch diameter classes so that total basal area at each measurement period could be calculated. This and other descriptive statistics of the plots, before and after thinning in 1949, are shown in table 1. Along with the d.b.h. and height measurements, the crown class of crop trees was also determined and recorded in 1949, 1954, 1959, 1964, and 1974. Periodic increments of crop trees were calculated as the differences between values of measured (d.b.h. and height) or derived (cross-sectional area and volume) growth expressions from one measurement to the next. Total and merchantable cubic volumes of crop trees were computed with Faurot's (1977) tree volume equations. Merchantable cubic volumes were computed to a 4-inch top for all crop trees that were 5.0 inches d.b.h. and larger. The total volumes per acre of crop trees and all trees on each plot were estimated with Faurot's (1977) stand volume equation for western larch.

Data Analysis

Treatment factors (thinning rule and method of removal) were confounded by lack of replication; therefore, differences between thinning rules and between removal methods could not be statistically tested. Although plot values were summarized for reference purposes, statistical analyses were keyed to growth responses of individual crop trees. Regression methods were used in these analyses.

Regression screens were made to identify variables and combinations of variables that significantly explained variation in individual crop-tree growth responses. Growth responses used as dependent variables in the regression screens were periodic increments of: (1) d.b.h. (PDI); (2) cross-sectional area (CSI); (3) height (PHI); (4) total cubic volume (PVI); and (5) merchantable cubic volume (PMVI). Growth responses were analyzed for the 25-year period, 1949–74, and for the last 10 years of measured growth, 1964–74. Independent variables considered in the analyses were d.b.h., cross-sectional area, height, crown class, tree volume at the beginning of the growth period, and treatment. Treatment (thinned or unthinned) was handled as a dummy variable in the analysis, as was the crown class of the tree.

The regression screens indicated that the cross-sectional area in square inches of the subject tree in 1964 (CSA64) was highly related to all subsequent growth responses except height increment. It explained 50 to 60 percent of the variation in d.b.h. increment (PDI), 60 to 90 percent of the variation in volume increment (PVI and PMVI), and 35 to 80 percent of the

Table 1.—Plot values before and after thinning in 1949 (before-thinning values are in parentheses)

Plot	Treatment	Total stand: No. trees per acre		Total stand: Mean d.b.h.		Total stand: Basal area per acre		Crop trees only: Trees per acre	Crop trees only: Mean d.b.h.	Crop trees only: Mean height	Crop trees only: Basal area per acre	Crop trees only: Volume per acre
				Inches		Ft^2			*Inches*	*Feet*	Ft^2	Ft^3
1	D+4, poison	(1,586)	—	(3.4)	—	(103)	43	198	5.3	44	34	610
2	D+4, axe	(1,386)	—	(3.8)	—	(111)	54	188	5.6	50	33	664
3	Crown, poison	(1,410)	—	(3.9)	—	(118)	71	168	5.8	48	32	656
4	Crown, axe	(1,886)	—	(3.2)	—	(106)	65	174	5.7	47	34	665
5	Unthinned	(1,668)	1,668	(3.9)	3.9	(135)	135	164	6.0	52	36	753

variation in cross-sectional area increment (CSI) from plot to plot for the 10-year period (1964-74). No other independent variable added appreciably to the variation explained. Because periodic height increment was poorly explained, it was dropped as a response variable in the analysis.

Percentages of variation explained for the 25-year period (1949-74) were similar to the 10-year period (1949-59) for regressions of growth on cross-sectional area in 1949 (CSA49). One exception was periodic diameter increment (PDI), where only 19 percent of the variation was explained by the linear model. This was expected. Earlier studies (Cole and Stage 1972) have shown that linear models are relatively ineffective for describing periodic diameter growth of individual trees for intervals longer than about 10 years; therefore, only 10-year PDI (1964-74) was further evaluated. Since many of the crop trees in the first 15 years of the study were below the d.b.h. threshold (5 inches) for computing merchantable volume, PMVI was also evaluated only for the last 10 years of the study.

Because initial tree size was not independent of the thinning rules used in this study, covariance analysis of regression models was used to separate treatment effects from interaction effects of the treatments and covariate—so that increment differences in d.b.h., cross-sectional area, and volume could be tested for statistical significance. Numerical crop-tree mortality was examined by 5-year periods over the years 1949-74 and tested for difference between thinning and no thinning by a t-test of mean difference.

RESULTS AND DISCUSSION

Mean Plot Values

Plot values of d.b.h., height, basal area, and stem volume do not clearly show relative crop-tree growth responses to the treatments (table 2). Possible reasons for this are: (1) lack of replication in the study design, (2) differences in stand density before thinning and related differences in the initial number and mean diameter of crop trees, (3) mortality differences, and (4) differences in basal area of other trees left on the plots after thinning. Despite these limitations, the plot values of table 2 provide some reference value in evaluating crop-tree response, and are useful for evaluating the total stand response to the D+4 and Crown thinning rules, as discussed later.

Crop-Tree Response

MORTALITY

Mortality of crop trees from 1949-74 averaged 9 percent in the thinned plots and 4 percent in the unthinned plot. To statistically test these differences, the trees-per-acre data of table 2 were apportioned to 5-year mortality counts and weighted to represent equal plot area on which mortality occurred, as follows:

Period	Thinned	Unthinned
	Trees per acre	
1949-54	3.25	0
1954-59	3.25	0
1959-64	2.50	1.0
1964-69	3.75	1.0
1969-74	3.75	1.0

Table 2.—Plot values of treatments in 1949, 1959, 1964, and 1974

			All trees		Crop trees only				
Plot	Treatment	Year	Basal area per acre	Total stand vol./acre[1]	Basal area per acre	Trees per acre	Mean d.b.h.	Mean height	Total vol. per acre[1]	Merch vol. per acre[2]
			Ft.	*Ft.*	*Ft.*		*Inches*	*Feet*	*Ft.*	
1	D+4, poison	1949	43	681	33	198	5.1	44	610	455
		1959	58	1,148	47	188	6.6	55	1,077	866
		1964	72	1,607	54	182	7.3	62	1,551	1,150
		1974	88	2,122	64	172	8.1	67	1,959	1,560
2	D+4, axe	1949	54	792	33	188	5.6	50	664	447
		1959	66	1,425	43	176	6.7	60	963	848
		1964	77	1,832	49	176	7.2	65	1,431	1,078
		1974	89	2,274	56	168	7.9	71	1,822	1,480
3	Crown, poison	1949	71	1,227	32	168	5.8	48	656	464
		1959	88	1,869	42	166	6.8	59	945	817
		1964	94	2,200	47	164	7.3	65	1,375	1,042
		1974	108	2,722	56	156	8.0	70	1,740	1,414
4	Crown, axe	1949	65	1,100	34	174	5.7	47	665	412
		1959	83	1,673	46	172	7.0	56	1,026	867
		1964	98	2,152	54	170	7.5	61	1,442	1,130
		1974	111	2,717	65	166	8.3	68	1,909	1,604
5	Unthinned	1949	135	2,527	36	164	6.0	52	753	505
		1959	147	3,281	45	164	7.1	62	1,069	900
		1964	156	3,763	49	160	7.4	67	1,458	1,118
		1974	162	4,257	57	158	8.0	73	1,802	1,468

[1]Estimated from western larch stand volume equation (Faurot 1977).
[2]Volume to 4-inch top, in cubic feet, calculated from tree-volume equation (Faurot 1977).

A t-test of mean difference of these 5-year mortality counts revealed that the average crop-tree mortality in the thinned plots was significantly greater (0.05 level) than in the unthinned plot. Increased exposure to wind and snow damage likely contributed to the higher mortality of thinned plots. Plot records showed that snow-bent and wind-damaged trees were more common in the thinned plots than in the control in the first 10 years after thinning, and many of the snow-bent trees died. Although the extent of crop-tree mortality probably had minimal effect on the growth of surviving trees, plot volumes could have been affected.

GROWTH

Diameter Increment of Crop Trees

Differences in periodic crop-tree diameter growth (PDI) between thinned and unthinned plots could only be tested with linear models for a 10-year growth period. The best linear model: PDI = f (D, CSA64, and D × CSA64) explained only 35 percent of the variation in PDI for the period 1964–74, thus is not intended for prediction. Nevertheless, the model was sufficient for testing significance of the explanatory variables, particularly the contribution of D, the dummy variable, which distinguished between thinned and unthinned plots.

Periodic diameter increments (PDI) of crop trees in thinned plots were significantly greater (0.05 level) than those in the unthinned plot, according to covariance analysis of the regression model of figure 1. However, the 0.17-inch greater average PDI in thinned plots in the last 10 years of measurement was only about half as great as in the first 10 years of the study (Roe and Schmidt 1965). Over the entire 25-year period, the diameter increase of thinned crop trees was less than 1 percent greater than crop trees in the unthinned plot. As is common with most thinnings, the declining diameter growth after the first 10 years indicates that the plots needed rethinning to maintain diameter growth rates of crop trees.

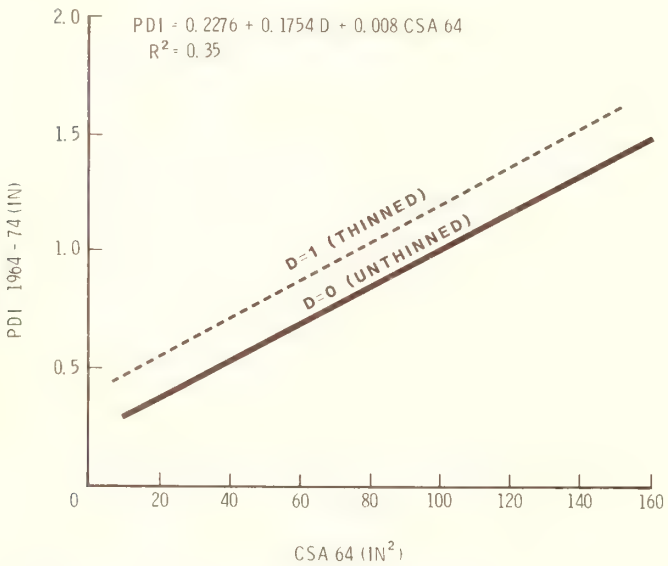

Figure 1.— Ten Year periodic diameter increment (PDI) of individual crop trees in thinned and unthinned plots in relation to CSA64—cross-sectional area at breast height in 1964.

The level and trend of the diameter-growth response of crop trees was also considered by comparing the mean d.b.h. values of table 2 with curves of potential d.b.h. and diameter growth of western larch developed by Schmidt and others (1976). For the appropriate site index and stand age of this study, the potential d.b.h. curves indicated that the present crop-tree d.b.h. of thinned plots was only 84 percent of its potential, while the unthinned plot was at 82 percent. The potential diameter growth curve indicated that the most recent 10-year diameter growth of crop trees in thinned plots was 70 percent of potential, compared to 55 percent for the unthinned plot. Thus, the crop-tree thinnings have clearly slowed the decline in diameter growth shown by the unthinned stand. But attained d.b.h. and recent diameter growth of the thinned plots still is only 84 and 70 percent of potential, respectively—indicating that other methods and schedules of thinning might have been more effective in this pole stand. Also, considerably earlier thinning would probably have better helped crop trees to attain their potential diameter growth.

Cross-Sectional Area Increment of Crop Trees

Cross-sectional area increment (CSI) of crop trees was significantly greater (0.05 level) in thinned plots than unthinned for both the overall 25-year growth period and the last 10-year period (figs. 2 and 3). But the difference is narrowing because CSI is declining faster in thinned plots. This was determined by comparing growth trends The average periodic cross-sectional area increment of thinned and unthinned plots of figures 2 and 3 were calculated as average annual increments for both growth periods. The average annual increment of the most recent 10-year period was expressed as a ratio of the overall 25-year growth period. On this basis, the average annual rate of CSI of thinned crop trees in the last 10 years was only 82 percent of their overall 25-year annual CSI rate, compared to 93 percent for crop trees of the unthinned plot.

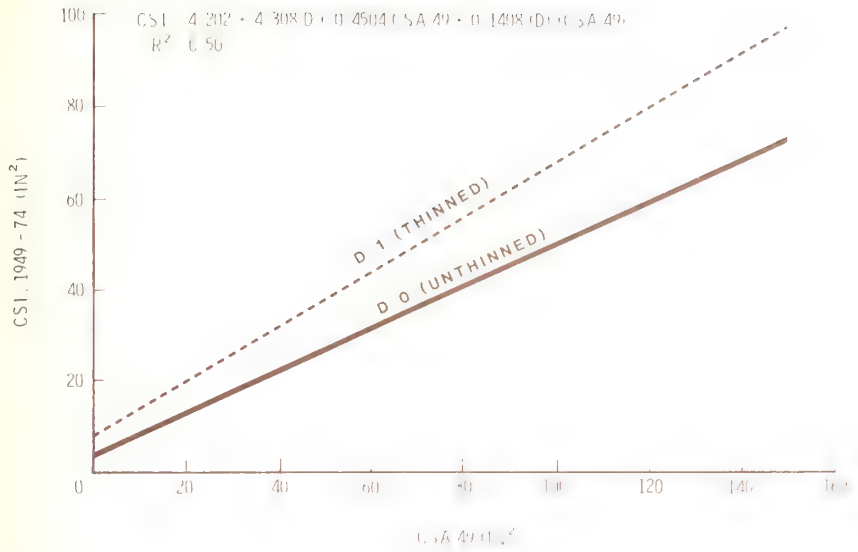

Figure 2.—Twenty-five-year periodic cross sectional increment (CSI) of crop trees in thinned and unthinned plots in relation to CSA49—cross-sectional area at breast height in 1949.

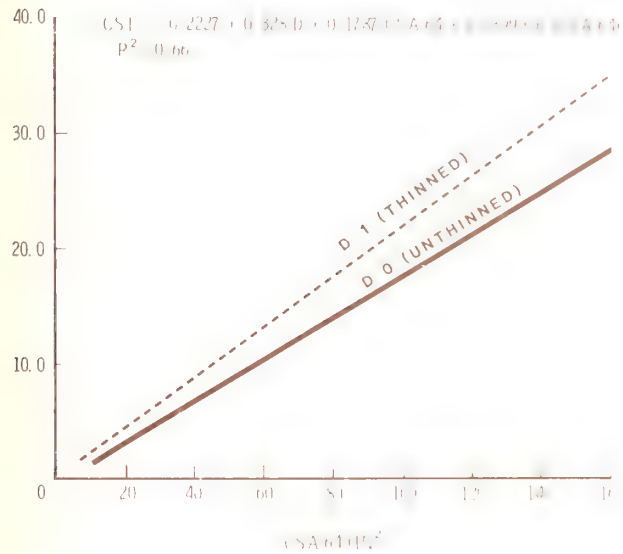

Figure 3.—Ten-year periodic cross sectional increment (CSI) of individual crop trees in thinned and unthinned plots in relation to CSA64—cross-sectional area at breast height in 1964.

Volume Increment of Crop Trees

Merchantable and total cubic volume increments of individual crop trees were significantly greater (0.05 level) in thinned than in unthinned plots. This was determined with regressions fitted to: (a) merchantable cubic volume growth for the 10-year period, 1964–74 (fig. 4); (b) total cubic volume growth for the 25-year period, 1949–74 (fig. 5); and (c) total cubic volume growth for the 10-year period, 1964–74 (fig. 6). Although statistically significant, these greater crop-tree volume increments in thinned plots were not greatly different in absolute units of measurement (figs. 5 and 6). To get an idea of the trend of crop-tree volume growth in thinned plots versus the unthinned plot, the regressions of figures 5 and 6 were solved for a typical tree of 8 inches d.b.h. (50 in^2) and converted to an annual growth basis. The absolute difference in thinned and unthinned conditions was 0.11 ft^3/yr for the overall 25-year growth period, but only 0.04 ft^3/yr for the last 10-year growth period. Although these differences indicate a declining volume-growth trend of crop trees, they should not be transposed to volume per acre differences. To assess volume per acre response of the thinning rules, direct comparisons of merchantable and total cubic volumes per acre of the thinned and unthinned plots are more appropriate.

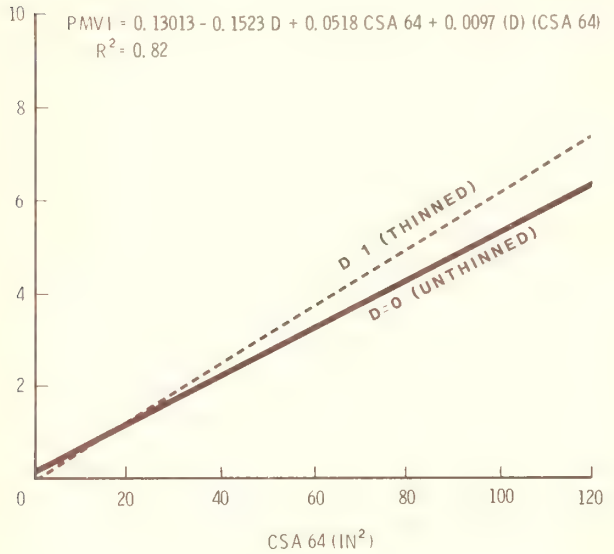

Figure 4.—Ten-year periodic merchantable volume increment (PMVI) to a 4-inch top of crop trees in thinned and unthinned plots in relation to CSA64— cross-sectional area at breast height in 1964.

Merchantable cubic volumes to a 4-inch top and total cubic volumes of crop trees are summarized on a per-acre basis in table 2. At last measurement, standing merchantable and total volumes per acre of crop trees were greater in three of the four thinned plots than in the unthinned plot. And growth in all the thinned plots in the last 10 years exceeded the unthinned plot by an average of 64 ft^3/acre for both merchantable and total volumes. But differences in standing volume and recent volume increment of crop trees, attributable to thinning, might be more apparent than real—particularly in regard to merchantable volume. This is suggested by table 3 which summarizes differences in number, size, mortality, ingrowth, merchantable volume growth, and standing merchantable volume of crop trees of thinned versus unthinned plots.

Crop-tree mortality and ingrowth was higher in thinned plots in the last 10 years (table 3). But, when the effects of dissimilar stocking and ingrowth differences are removed, the apparent thinned plot growth advantage of 64 ft^3/acre is reduced to a relatively insignificant 20 ft^3/acre. Because of these problems in using absolute units of comparison, recent volume-growth trends are considered to be less ambiguous for assessing thinning response.

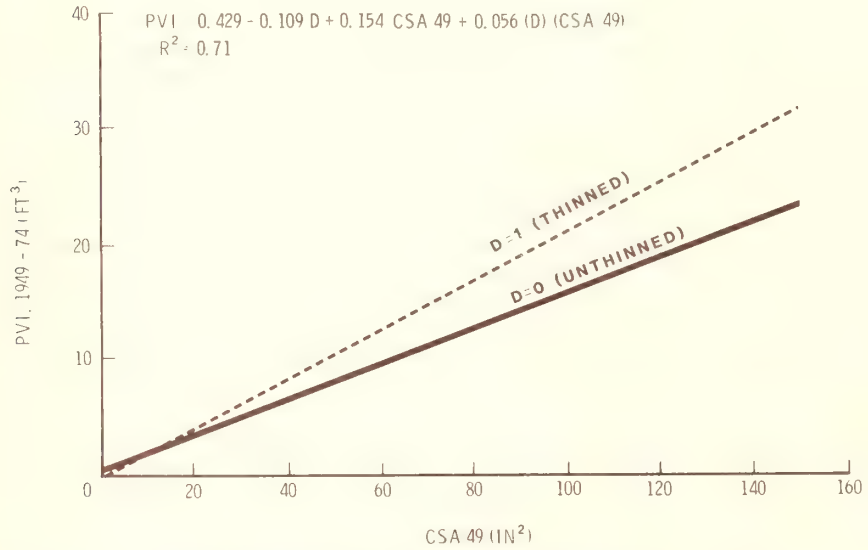

Figure 5.—Twenty-five-year periodic volume increment (PVI) of crop trees in thinned and unthinned plots in relation to CSA49—cross-sectional area at breast height in 1949.

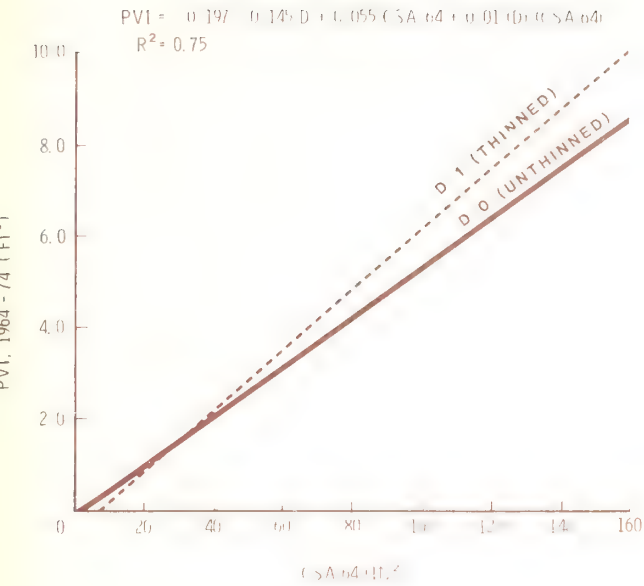

Figure 6.—Ten-year periodic volume increment (PVI) of crop trees in thinned and unthinned plots in relation to CSA64—cross-sectional area at breast height in 1964.

Table 3.—Complicating factors in comparing merchantable volume growth per acre and standing volume per acre of crop trees in thinned and unthinned plots

	Average		Submerchantable						Merchantable volume	
	d.b.h.	Stocking	stocking		Ingrowth[1]		Mortality	Stocking	Growth[2]	Standing
Treatment	1949	1949	1949	1974	1949-74	1964-74	1949-74	1974	1964-74	1974
	Inches				Trees per acre				Ft³/acre	
Thinned	5.6	182	72	7	50	10	16	166	414	1,515
Unthinned	6.0	164	66	11	48	0	6	158	350	1,468

[1]Number of trees per acre in the period attaining the 5 inches d.b.h. minimum used for computation of merchantable cubic volume to a 4-inch top.

[2]Merchantable cubic volume to a 4-inch top was calculated for all crop trees 5 inches d.b.h. and larger, and expressed on a per-acre basis.

Trends of periodic merchantable and total cubic volume increment were compared for thinned versus unthinned plots. These were determined from table 2 by expressing the average annual growth of the last 10 years as a ratio of the average annual growth for the overall 25-year period. The ratio for merchantable volume growth was 0.97 in thinned plots and 0.91 in the unthinned control; but, when the merchantable volume ingrowth effect was removed, the ratio for thinned plots was also 0.91. Therefore, the trend of annual merchantable volume growth was the same in both the thinned and unthinned plots in the last 10 years of the study, both declining to about 91 percent of their overall 25-year averages. Like merchantable volume increment, the trend of total cubic volume increment of crop trees declined in the last 10 years in both thinned and unthinned plots. The trend ratio was 0.73 for thinned plots and 0.84 for the unthinned plot. The lower ratio of the thinned plots indicates that recent crop-tree growth in total cubic volume per acre is declining faster, relative to its earlier rate, in thinned plots than in the unthinned plot.

The observation that growth in total cubic volume per acre for crop trees is declining faster than merchantable volume per acre and that both measures of growth are declining from earlier levels is consistent with general thinning experience. Thinning can redistribute volume growth per acre among different numbers of crop trees but cannot increase it unless growth is measured in merchantable volume instead of total cubic volume. Therefore, although the greater volume growth of thinned crop trees in this study was statistically significant, the apparent per-acre growth advantage is not practically significant. This is so because, when equal numbers of trees, growth trends, and ingrowth are considered, differences in both merchantable and total cubic volume per acre of thinned versus unthinned plots were not large enough to be of much practical importance.

Total Stand Response

After 25 years of total stand development, the D+4 and Crown thinning plots continue to trail the unthinned control in net total basal area per acre, in net total volume per acre, and in net 25-year periodic volume increment, as shown in table 4. Nearly all noncrop trees were submerchantable, so net merchantable volumes per acre of all trees in the plots were not relevant.

Table 4.—Average net stand values 25 years after crop-tree thinning by the D+4 and Crown Rules, compared to an unthinned control

Treatment	Average basal area per acre		Average volume per acre		25-year net volume increment per acre	
	Ft^2	Pct. of control	Ft^3	Pct. of control	Ft^3	Pct. of control
D+4	89	55	2,198	52	1,462	84
Crown	110	68	2,719	64	1,556	90
Unthinned control	162	100	4,257	100	1,730	100

Table 5.—Normal yield volume table for western larch in total cubic feet per acre of all trees 0.6 inch d.b.h. and larger[1 2 3]

Age	Site index					
	30	40	50	60	70	80
	Total cubic feet per acre					
20	165	246	336	434	538	648
30	548	819	1,118	1,443	1,790	2,157
40	999	1,494	2,040	2,632	3,265	3,934
50	1,433	2,142	2,926	3,775	4,682	5,643
60	1,823	2,724	3,721	4,801	5,955	7,176
70	2,164	3,235	4,419	5,701	7,071	8,521
80	2,462	3,680	5,026	6,484	8,043	9,692
90	2,721	4,067	5,555	7,167	8,890	10,714
100	2,948	4,407	6,019	7,765	9,632	11,608
110	3,148	4,705	6,427	8,292	10,285	12,394
120	3,325	4,970	6,788	8,757	10,862	13,090
130	3,482	5,205	7,109	9,172	11,376	13,710
140	3,623	5,415	7,397	9,543	11,836	14,264

[1]Standard error of estimate = 486 ft^3.
[2]Values within the block lines fall within the range of basic data.
[3]From Schmidt and others 1976.

Another way of looking at the total stand growth consequences of the age, site, and thinning rule interaction of this study is to compare the periodic annual increment (PAI) of treatment volumes to the normal yield table net volumes of Schmidt and others (1976). Their table (table 5) indicates that mean annual increments (MAI's), for site indices of 50 feet and 60 feet at 50 years, culminate at stand ages between 70 and 80 years. At the age (75 years) and site index (52) corresponding to this study, their table indicates total stand volumes at culmination of about 5,000 ft^3/acre—equivalent to an MAI of 67 ft^3/acre per year. Allowing for stand-to-stand variation, it appears that the unthinned plot culminated within a couple of years of age 75 years. This is indicated by the near-correspondence of the control plot PAI at age 75 years (69 ft^3/acre per year) with the normal yield table MAI at culmination. The much lower PAI's of total volume for the D+4 and Crown Rule thinnings (58 and 62 ft^3/acre per year, respectively) indicate that culmination of these plots will be delayed until age 110-120.

SUMMARY AND CONCLUSIONS

As in all thinning studies, we must distinguish between mean growth response of individual crop trees and growth per acre. The distinction is particularly important here because the thinning rules used in this study resulted in varying amounts of noncrop tree competition left on the plots after the crop-tree thinnings. After 25 years, this amounted to basal areas of about 28, 49, and 105 ft^2/acre, and volumes of about 300, 900, and 2,450 ft^3/acre for the D+4, Crown, and unthinned plots, respectively (table 2). Thus, the statistically greater response of diameter, cross-sectional area, and volume increments of crop trees in thinned versus unthinned plots (figs. 1-6) must be tempered with three qualifications:

1. Per-acre growth rates are declining in all plots, and—except for merchantable volume growth—declining faster in thinned plots.

2. At last measurement, thinned and unthinned plots were virtually the same in total and merchantable crop-tree volumes per acre when inequalities in crop-tree numbers and initial size are considered.

3. Basal area and total cubic volume of the total stand were still much lower in the thinned plots after 25 years—trailing the unthinned plot by 32 to 48 percent (table 4).

Because there is little practical difference in the size and per-acre volume of crop trees on thinned versus unthinned plots after 25 years, the D+4 and Crown Rules have not achieved the objective of appreciable growth redistribution onto the selected crop trees. Thus, unless significant increases in forage and water yields have resulted (these were not measured but could occur in thinned western larch stands), crop-tree thinnings of western larch stands beyond 50 years of age do not appear to be justified. Timber growth objectives for such even-aged western larch stands beyond 50 years of age are probably better served by uniform, low thinnings to stocking levels commensurate with the size and rotation objectives of the manager. Seidel (1977, 1980, 1982) documented the relationship of western larch growing stock levels to periodic individual tree growth and volume-per-acre growth for low thinning of both younger and comparable-aged stands on significantly better sites (SI_{50}=80) than involved in this study. It appears that the general nature of those relationships and their management implications would apply to low thinning of 50- to 75-year-old stands of lower site quality (SI_{50}=52), as involved here. A major difference in contemplating thinnings in overstocked western larch stands older than 50 years versus stands of about 30 to 35 years of age is the higher probability of some merchantable product recovery from the older stands. But this should not be misconstrued as a recommendation to delay thinnings in overstocked western larch stands until merchantable thinnings are possible. The attainment of adequate growth rates to meet the size and merchantable volume objectives of management is normally an overriding criterion for determining timing and method of thinning.

To assure acceptable growth from overstocked western larch stands, growing stock levels—appropriate to the size, volume, and rotation objectives of management (Schmidt and others 1976)—should normally be obtained by thinning at an earlier age than was done in this study. Ideally, such thinnings should be done in overstocked western larch stands when they are between 10 and 15 years old (Schmidt 1966). Such thinnings are obviously precommercial thinnings, but are a management investment to greatly increase the amount of usable wood volume at future harvest. If overstocked western larch stands are older than 50 years, and are not so seriously overstocked that merchantable products are precluded within a reasonable rotation period, it would probably be as well to leave them unthinned, unless increased forage and water yields justify the thinning.

In summary, the D+4 and Crown Rules of crop-tree thinning used in this study did not reduce competition enough to effectually increase growth rates of crop trees when compared to similar trees in the unthinned stand. But the crop-tree thinnings did result in markedly lower total cubic stand volumes. Other main detriments to using the D+4 and Crown Rules to thin western larch pole stands similar to those studied here appear to be the presence of significant amounts of other than crop trees left after thinning, and higher crop-tree mortality rates for the thinned plots. On the basis of the 25-year results of this study, the D+4 or Crown Rules are not recommended for thinning overstocked 50-year or older western larch stands. Low thinnings, preferably at a younger age, are recommended for overstocked western larch stands.

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A 50-year-old western larch stand, thinned in 1949 with the D+4 and Crown Rules of crop-tree thinning, showed less than 1 percent more diameter growth after 25 years than comparable trees in the unthinned control. Also, total volume of the unthinned plot was still 56 percent greater than that of any of the thinned plots. Earlier low thinning is recommended for this type stand.

KEYWORDS: thinning, thinning rules, crop-tree response, western larch, *Larix occidentalis*

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Corrosivity of Short-Term Forest Fire Retardants

Charles W. George
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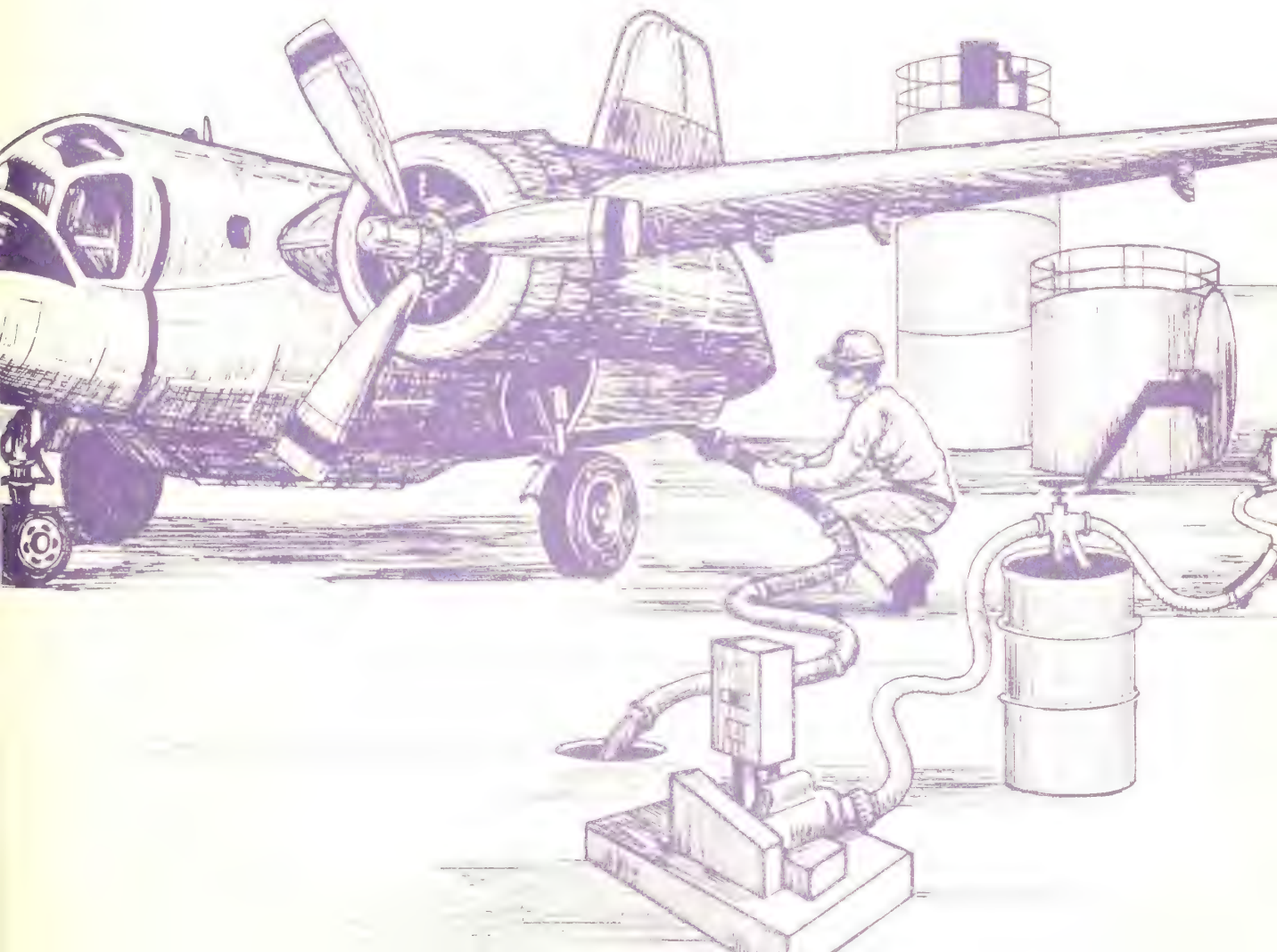

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RESEARCH SUMMARY

The corrosivity of several short-term fire retardants was determined by conducting 90-day uniform corrosion tests, determining uniform corrosion rates, and microscopically examining exposed coupons for occurrence of intergranular corrosion. Aluminum, brass, steel, and magnesium alloys were exposed under total and partial immersion conditions at 70° and 120° F. The susceptibility of aluminum 2024-T3 and magnesium Az-31-B to intergranular corrosion was determined when acceptable uniform corrosion rates were obtained. Results indicate that in terms of uniform corrosion, short-term retardants are generally less corrosive than present long-term retardants. Nevertheless, the frequency of intergranular corrosion warrants an effort to identify and add corrosion inhibitors to short-term retardants. Two short-term retardants were recommended without modification for use from fixed-wing aircraft. Because all short-term retardants caused intergranular corrosion on magnesium, it is recommended that they not be applied from helicopters with fixed tanks.

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INTRODUCTION

The increasing costs of long-term, salt-containing forest fire retardants have stimulated renewed interest in the use of thickened water or short-term retardant solutions. Unlike long-term retardants, short-term retardants do not contain a combustion-inhibiting chemical that is effective after the water has evaporated. Thus, short-term retardants are effective only as long as they retain adequate moisture.

Short-term retardants range from equally as effective as long-term retardants to infinitely less effective, depending on the conditions and tactical objectives of use. For example, the active salt in long-term retardants is of minimal value when the retardant is applied directly to the fire (direct attack), to knock down or cool the fire in support of ground personnel. When the retardant is to be applied 30 minutes or more before the fire will reach the treated fuel (indirect attack), sufficient moisture may have evaporated so that without a combustion-inhibiting chemical, little or no value is obtained. Thus, for application in relatively close proximity (time or distance) to the fire's edge, short-term retardants may well be as effective as long-term retardarts.

Much attention has been given to the corrosivity of the salts in long-term retardants and their effects on aircraft structure, maintenance, and safety.

Damage to aircraft and retardant-mixing equipment has been evaluated on several occasions (Davis and Phillips 1965; Gehring 1974). Numerous laboratory studies have been conducted to determine the corrosivity of retardants to alloys commonly exposed, the effects of exposure, retardant properties, inhibitor systems, water quality, and other variables (USDA Forest Service 1964; Bradford 1973, 1974; Gehring 1974, 1978, 1980). Results of these studies and studies conducted at the Northern Forest Fire Laboratory[1] were considered in developing test procedures and establishing Forest Service requirements for long-term fire retardants. The requirements are based on the use for which the retardant system was developed (fixed-wing aircraft, helicopter, ground application) and the mixing, handling, use, and other factors (i.e., the need for the aircraft to sit loaded). The established corrosion requirements for long-term retardants are given in Forest Service specifications (USDA Forest Service 1982), and are summarized in table 1.

[1]Laboratory studies conducted at the Northern Forest Fire Laboratory under study plan 2107-75-500, George, C. W. and Johnson, C. W., "Laboratory investigation of fire retardant-caused corrosion" and results on file.

Because short-term retardants are usually thought of as relatively inert water-thickening agents, there has not been much concern about corrosivity. In the early development and use of retardants in the mid- 50's and early 60's, however, it was found that some short-term retardants, such as Algin-gel, were severely corrosive (Davis and Phillips 1965).

Although specifications for short-term retardants have not been established, the use and exposure of aircraft, mixing, storage, and handling equipment is often similar to that of long-term retardants; therefore, the same corrosion requirements may be applicable.

The present study was conducted to determine the corrosiveness of short-term fire retardants and to compare their performance under established long-term fire retardant corrosion test procedures to existing standards. The results of the corrosion testing of present short-term retardant formulations will be used to determine whether their characteristics warrant development of qualification procedures or criteria different from or supplemental to those applied to long-term retardants.

STUDY DESCRIPTION

The study consisted of a series of tests to quantify the uniform corrosion rate and intergranular corrosion susceptibility of selected alloys exposed to various short-term retardant formulations. Uniform corrosion is corrosion spread evenly over large areas of the exposed surfaces. The amount of damage caused by the attack is ordinarily determined by comparing the thickness of the corroded metal with that of an undamaged specimen. (The corrosion rate is expressed as the thickness of metal removed as a function of time, usually thousandths of an inch [mils] per year [mpy].) Intergranular corrosion occurs at the boundaries of the metal grains, first consuming the material between the grains and then attacking the grains themselves. Intergranular corrosion, like pitting, causes a loss of strength and ductility disproportionate to the amount of metal destroyed.

The specific alloys used are identified in table 1 and were a result of previous field and laboratory studies, including an assessment of the existing fire retardant-caused corrosion problem.

The uniform corrosion rates were determined using standard weight-loss methods in which coupons of the specific alloys were exposed to the short-term retardants under a variety of conditions (total immersion, partial immersion, and 70° F and 120° F solution

Table 1.—Corrosion requirements for forest fire retardants (USDA Forest Service specifications)[1]

	2024-T3 aluminum				4130 steel				Yellow brass				Az-31-B magnesium			
	70° Total	70° Partial	120° Total	120° Partial	70° Total	70° Partial	120° Total	120° Partial	70° Total	70° Partial	120° Total	120° Partial	70° Total	70° Partial	120° Total	120° Partial
Premix components																
Liquid components and concentrates	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	[2]5.0	[2]5.0	[2]5.0	[2]5.0
Mixed retardants																
Fixed-wing or helicopter with bucket	[2]2.0	[2]2.0	[2]2.0	[2]2.0	2.0	5.0	2.0	5.0	2.0	5.0	2.0	5.0	[4]—	[4]—	[4]—	[4]—
Helicopter with internal or fixed tank	[2]2.0	[2]2.0	[2]2.0	[3]2.0	2.0	5.0	2.0	5.0	2.0	5.0	2.0	5.0	[3]2.0	[3]2.0	[3]2.0	[3]2.0
Ground application	2.0	2.0	2.0	2.0	2.0	5.0	2.0	5.0	2.0	5.0	2.0	5.0	[4]—	[4]—	[4]—	[4]—

[1]All corrosion rates will be determined by 90-day weight loss. All uniform corrosion rates are the maximum allowable average of at least three replicates. In addition, the standard error of the mean shall not exceed 0.5 for total immersion or 1.0 for partial immersion. (The number of replications may be increased to decrease the standard error if all values are retained to calculate the average and the standard error.)

$$s_m = \sqrt{\frac{x^2 - n\,X^2}{n}}$$

[2]If submitted for "helicopter with internal or fixed tank"; for all other types, refer to footnote 4.
[3]Intergranular corrosion tests will be performed; no intergranular corrosion is allowed.
[4]Test shall be conducted for performance information.

temperatures), and the loss of weight of the coupons determined. After weight-loss determinations were completed, the coupons were sliced, mounted, polished, and etched using standard metallurgical techniques, and examined microscopically for intergranular corrosion.

The short-term retardants were selected either from those currently being used or those being evaluated in the field by fire management agencies. The concentrations or mixing ratios to be used in the study were similarly selected. Two retardants—Gelgard® and Tenogum® —were also included because of their previous history of use in Alaska and Canada with water-scooping aircraft such as the CL-215 and PBY (the short-term retardant being injected during the water-skimming operation). Table 2 lists the retardants included in the study, the concentration or mixing ratio, and the manufacturers or distributors.

Table 2.—Short-term fire retardants selected for the study

Short-term retardant	Concentration or mixing ratio
	Percent by weight
Absorbex 2020 SLS Absorbent Polymers, Inc.	0.66 and 0.75
Short-Stop (SGP502S) Merryhill Co. (Henkel Corporation starch)	0.75 and 1.0
Fire-Trol ST-poly, Poly-Trol Chemonics Industries (Nalco Chemical Co. synthetic polymer)	0.66 and 1.5
Fire-Kill I Sanitek Products, Inc. (Kelco Xanthan gum)	1.0
Fire-Kill II Sanitek Products, Inc. (Xanthan gum and synthetic polymer)	0.75 and 1.0
Fire-Trol AC-1 Chemonics (Stein, Hall & Co., Inc. guar gum)	0.50 and 1.0
Gelgard Dow Chemical Co.	0.24
Tenogum Charles Tennant & Co., Ltd.	0.35

METHODS

Methods used to determine corrosive characteristics of short-term fire retardants were similar to those developed for long-term fire retardants and adopted in Forest Service specifications (USDA 1982). The procedure calls for total and partial immersion of separate coupons of aluminum, steel, brass, and magnesium in freshly prepared retardant samples for 90 days at temperatures of 70° ± 5° F (21.1° ± 2.8° C) and 120° ± 5° F (48.9° ± 2.8° C). Test procedures for long-term retardants include three replications (coupons) for each immersion condition (total and partial) and temperature, and each of the four alloys. These replications are required because of the high corrosion rates and the poor

eproducibility often accompanying the testing of long-erm retardants. Single specimens were used for this tudy, however, because short-term retardants were ex-pected to exhibit relatively low corrosivity. (Single pecimens still required 4 alloys × 2 immersions × 2 emperatures, or 16 corrosion specimens, for each short-erm retardant and mixing ratio selected.)

Short-term retardants were designed to be used im-nediately upon mixing, and hence do not normally con-ain spoilage inhibitors that facilitate 90-day immersions. Test procedures were therefore modified. The short-term etardant mixture was replaced weekly, to minimize etardant spoilage and degradation.

Test coupons were 1 by 4 by 1/8 inch (2.5 by 10.2 by .32 cm), with a small hole at one end for suspending he coupon in the retardant solution. Each coupon was ermanently marked, and the length, width, and height neasured to 0.001 cm. The coupons were first degreased vith an all-purpose cleaner ("409") and then cleaned to emove other foreign substances and remaining oxides sing the procedure shown in table 3. Coupons were then inse in distilled water, ovendried at 50° to 60 C, and veighed to 0.1 mg. Cleaned coupons were handled with loves or forceps to prevent contamination. Each coupon vas positioned in a 1-quart glass jar containing either 00 or 800 ml of the retardant to be tested. The jars ontaining 800 ml were used for total immersion ex-osures, where the coupon was completely immersed. Those containing 400 ml were used for the partial im-nersion test where exactly 5 cm of the coupon length vas immersed. In each case, the coupon was positioned n such a way that it did not touch the side or the bot-om of the jar. Each jar was then closed with a tight-itting lid to prevent evaporation and placed in emperature- controlled incubators. Weekly during the 0-day exposure period the retardant was removed and eplaced with fresh retardant. Figure 1 shows two test amples containing coupons, one partially immersed and ne totally immersed.

At the end of the 90-day test period, the coupons were emoved, rinsed under tap water to remove any remain-ng retardant, and cleaned using standard cleaning pro-edures, as presented in table 4. The cleaning procedure iven in the table was carefully repeated until films or

Figure 1.—Corrosion test coupons partially and totally immersed in two short-term retardants.

products of corrosion were removed, being sure not to remove any original alloy. An unexposed control coupon of each of the alloys included in the study was prepared and cleaned in the same manner to determine loss of metal during the cleaning procedure. Following cleaning, all coupons were rinsed in distilled water, air-dried, and weighed to 0.1 mg.

The corrosion rate in mils per year (mpy) for each coupon was determined using the following equation and values for alloy density:

$$\text{Uniform corrosion rate (mpy)} = \frac{[\text{Initial wt.} - \text{final wt.} - \text{wt.loss by control(mg)}] \times 534}{\text{area(in}^2) \times \text{time(h)} \times \text{alloy density(g cm}^{-3})}$$

where the density of:

2024-T3 aluminum = 2.77 gm/cm^3
4130 steel = 7.86 gm cm
yellow brass = 8.47 gm/cm
Az-31-B magnesium = 1.77 gm/cm^3

Table 3.—Procedure for cleaning unexposed coupons

Alloy	Chemical	Time	Temperature	Remarks
		Minutes		
Aluminum (2024-T3)	70% HNO_3	2-3	70 F (21 C)	Follow with light scrubbing using non-metalic brush
Yellow brass	20% HCl	2-3	70 F (21 C)	ditto
Steel (4130)	20% HCl	3-5	Cold	ditto
Magnesium (Az-31-B)	19% $Na_2Cr_2O_7$ or 21 K_2Cr_2O in dist H_2O	15	Boiling	ditto

Table 4.—Procedure for cleaning exposed corrosion coupons

Alloy	Chemical	Time	Temperature	Remarks
		Minutes		
Aluminum (2024-T3)	70 % HNO_3	2-3	70 F (21°C)	Follow with light scrub using non-metallic brush[1]
Aluminum (2024-T3)	2 % $Na_2Cr_2O_7$ in 5% H_3PO_4	10	175°-185°F (79°-85°C)	Use when film resists HNO_3 treatment. Alternate 2 treatments as needed.
Yellow brass	15-20% HCl	2-3	70°F (21°C)	Follow with light scrub using non-metallic brush[1]
Steel (4130)	5% $SnCl_2$ + 2% $SbCl_3$ in conc HCl	3-5	Cold	ditto
Magnesium (Az-31-B)	19% $Na_2Cr_2O_7$ or 21% $K_2Cr_2O_7$ in dist H_2O	15	Boiling	ditto

[1]A rubber stopper can be used to scrub coupons with corrosion products which are hard or extremely difficult to remove with a brush.

Figure 2 shows examples of coupons following final cleaning that have been exposed to short-term retardant during the 90-day corrosion test.

When the 90-day uniform corrosion tests were completed and the results scrutinized, selected test coupons were prepared for intergranular corrosion determination. Intergranular corrosion inspections of aluminum and magnesium coupons exposed to the different types of short-term retardants and mixing ratios were made only when uniform corrosion tests indicated that acceptable levels of corrosion were experienced. (Acceptable corrosion levels are shown in table 1.) Intergranular corrosion requirements exist only for aluminum and magnesium alloys because of their use in structural members and other critical components of fixed-wing aircraft and helicopters. (No intergranular corrosion to aluminum coupons is allowed for retardants formulated for fixed-wing aircraft application; no intergranular corrosion to either aluminum or magnesium is allowed for application from helicopters equipped with fixed tanks.)

Standard procedures for determining the occurrence of intergranular corrosion were used in the study. Intergranular corrosion was determined by qualified laboratories under contract (Ocean City Research Corp., Ocean City, N.J.; and Magnaflux Quality Services, Los Angeles, Calif.) Coupons were sliced as shown in figure 3, mounted, polished to 0.3 micron alumina finish, and etched with appropriate reagents using standard metallurgical techniques and examined microscopically up to a magnification of 600 X. If intergranular corrosion was present, its location (the section where it was identified), as well as the depth of intergranular attack and the magnification, were noted. Figure 4 shows a coupon prior to preparation for intergranular examination and specimens that have been prepared for microscopic inspection. Examples of typical intergranular corrosion attack to aluminum and magnesium are illustrated in the photomicrographs in figure 5.

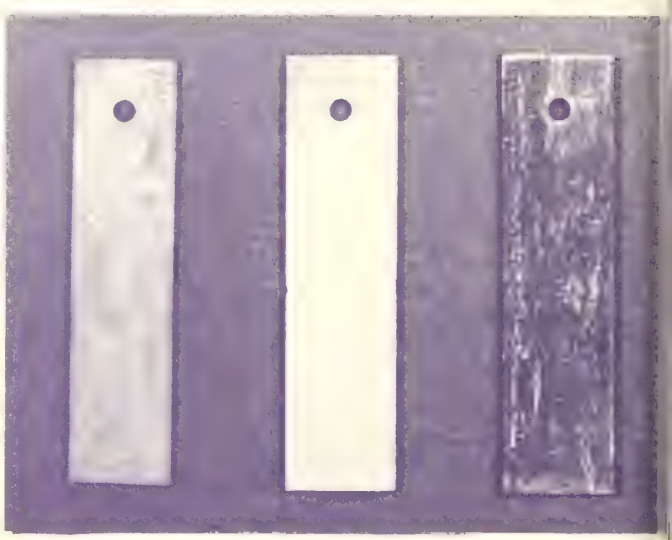

Figure 2.—Examples of exposed corrosion coupons (left coupon aluminum, totally exposed, 2.4 mpy: center coupon aluminum, partially exposed, 4.3 mpy; right coupon, Mg, 10.4 mpy).

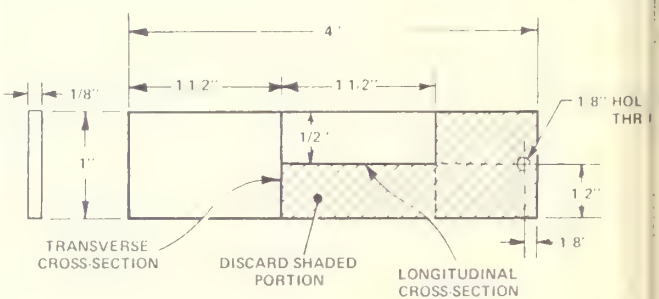

Figure 3.— Diagram of a coupon showing the location of the slice and surfaces to be inspected for intergranular corrosion.

Figure 4.—Coupons which have been cut, mounted, polished, and etched for microscopic examination for intergranular corrosion alongside an unexposed coupon.

Figure 5.—Photomicrographs of aluminum 2024-T3 exposed to Fire-Trol ST-poly (200 X), left; and magnesium Az-31-B exposed to Fire-Kill II (500 X), right.

RESULTS AND DISCUSSION

The corrosion rates determined for the controls and each of the formulations and concentrations tested are shown in table 5. Note that a single exposure was sometimes used to determine if the concentration or mix ratio of the short-term retardant affected corrosion. Also, a single exposure was used for those short-term retardants having significant use in the past, but which are no longer available or operationally used (Gelgard and Tenogum).

Tests for uniform corrosion indicated that the corrosion rate for short-term retardants is usually much less than the corrosion experienced with long-term fire retardants. Uniform corrosion rates for nearly all exposures to aluminum, steel, and brass alloys were less than 1 mpy compared to the maximum of 2 mpy allowed for long-term retardants (table 1). In all cases, the corrosion rate for magnesium Az-31-B was significantly higher than other alloys. Absorbex 2020-SLS had the highest rate on magnesium (10.3 mpy when totally immersed at 70° F). Both Short-Stop and Fire-Kill II had uniform corrosion rates on magnesium that exceeded the 2.0 mpy requirement established for long-term retardants formulated for application from helicopters equipped with fixed tanks. Corrosion rates on magnesium for these formulations, however, were in the 2 to 3 mpy range and are likely solvable.

An unexpected result was that intergranular corrosion was found on many aluminum and magnesium coupons exposed to short-term retardants. Table 6 provides a summary of those exposures resulting in intergranular corrosion, the location of the corrosion, and the depth of the intergranular attack. (Coupons inspected for intergranular corrosion were identified in table 5.)

The study indicates that although short-term retardants were expected to be less corrosive than long-term retardants, uniform corrosion rates can, as in the case with magnesium exposed to Absorbex 2020-SLS, be unusually high and exceed current allowable levels In addition, some short-term retardants that were relatively noncorrosive to aluminum or magnesium in tests of uniform corrosion exhibited intergranular corrosion which can have a potentially greater impact on the strength of structural members than uniform corrosion Based on these results, the corrosivity of short-term retardants should continue to be an important consideration in selection for operational use. Both long- and short-term retardants should meet similar corrosivity requirements, even though different corrosion-testing procedures may be required.

Absorbex 2020-SLS and Fire-Kill II were the only short-term retardants that met all current corrosion requirements for long-term retardants, and that probably are suitable for fixed-wing aircraft delivery. All short-term retardants were found to be corrosive (as defined by both uniform and intergranular corrosion tests) to magnesium, and should not be used from helicopters with fixed tanks. Experience suggests that because they do not contain high concentrations of salts, several short-term retardants may be inhibited to yield satisfactory corrosion performance.

Table 5.—Uniform corrosion weight loss test results for short-term retardants exposed for 90 days

	Exposure			
	Total immersion		Partial immersion	
	70° F	120° F	70° F	120°
	Corrosion rate in mils/year			
Controls[1]				
Distilled water				
2024-T3 aluminum	0.01	0.35	0.09	0.10
4130 steel	1.30	2.13	.65	1.98
Yellow brass	.02	.05	.02	.04
Az-31-B magnesium	.62	.33	.86	.85
Tap water				
2024-T3 aluminum	.72	.04	.16	.05
4130 steel	1.47	1.68	1.29	1.30
Yellow brass	.33	.01	.16	.02
Az-31-B magnesium	1.20	.55	.90	.55
Short-term retardants[2]				
Gelgard				
0.24% 2024-T3 aluminum	.18*			
Tenogum				
0.35% 2024-T3 aluminum	.02*			
Absorbex 2020-SLS				
0.75% 2024-T3 aluminum	.15*			
.66% 2024-T3 aluminum	.02*	.03*	.01*	.01
.66% 4130 steel	.47	.85	.73	.78
.66% Yellow brass	.12	.80	.14	.24
.66% Az-31-B magnesium	10.3	9.3	4.3	4.6
FT Ac-1				
0.1% 2024-T3 aluminum	.24*			
.5% 2024-T3 aluminum	.01*	.02*	.01*	.01
.5% 4130 steel	.22	.54	.37	.77
.5% Yellow brass	.05	.02	.03	.02
.5% Az-31-B magnesium	1.5*	.18*	.98*	.18
Short-Stop (Henkel SGP 502S)				
1.0% 2024-T3 aluminum	.07*			
.75% 2024-T3 aluminum	.30*	.64*	.39*	.49
.75% 4130 steel	.21	.19	1.1	1.2
.75% Yellow brass	.01	.42	.11	.27
.75% Az-31-B magnesium	2.7*	1.8*	2.5*	2.9*
FT St-Poly				
Colored				
1.5% 2024-T3 aluminum	.02*			
Uncolored				
1.5% 2024-T3 aluminum	.03*			
.66% 2024-T3 aluminum	.03*	.09*	.02*	.16
.66% 4130 steel	.12	.33	.53	.73
.66% Yellow brass	.01	.04	.01	.03
.66% Az-31-B magnesium	1.7*	1.6*	1.3*	.52
Fire-Kill II				
1.0% 2024-T3 aluminum	.01*			
.75% 2024-T3 aluminum	.01*	.07*	.01*	.01
.75% 4130 steel	.08	.26	.29	.89
.75% Yellow brass	.01	.05	.01	.03
.75% Az-31-B magnesium	3.0*	2.3*	2.2*	.18
Fire-Kill I				
1.0% 2024-T3 aluminum	.01*			

[1]Average of three replications at each exposure on controls.
[2]One coupon tested at each exposure on short-term retardants; * indicates coupons examined for intergranular corrosion.

Table 6.—Results of examinations for intergranular corrosion[1]

Sample	Alloy	Exposure	Observation and/or depth of intergranular attack (inches)
		F temp/ immersion	
Gelgard	Al	70 total	None observed
Tenogum	Al	70 total	None observed
Absorbex 0.75	Al	70 total	None observed
.66	Al	70 total	None observed
	Al	120 total	None observed
	Al	70 partial	None observed
	Al	120 partial	None observed
FT AC-1 1.0	Al	70 total	None observed
.5	Al	70 total	None observed
	Al	120 total	None observed
	Al	70 partial	None observed
	Al	120 partial	Intergranular attack 0.0016 face of panel (trans. and long.)
	Mg	70 total	Intergranular attack - 0.0020 face of panel (trans. long.)
	Mg	120 total	Intergranular attack - 0.0015 face of panel (trans. long.)
	Mg	70 partial	Intergranular attack - 0.0018 face of panel (trans. long.)
	Mg	120 partial	Intergranular attack - 0.0018 face of panel (trans. long.)
Short-Stop 1.0	Al	70 total	None observed
.75	Al	70 total	Intergranular attack 0.0102 long.; 0.0220 trans. edge
	Al	120 total	Intergranular attack - 0.0062 edge attack
	Al	70 partial	Intergranular attack - 0.0400 edge attack
	Al	120 partial	None observed
	Mg	70 total	Intergranular attack - 0.0044 body; 0.0078 edge
	Mg	120 total	Intergranular attack - 0.0032 body; 0.0088 edge
	Mg	70 partial	Intergranular attack - 0.0056 body; 0.0084 edge
	Mg	120 partial	Intergranular attack - 0.0036 body; 0.0032 edge

Table 6.—(con.)

Sample	Alloy	Exposure	Observation and/or depth of intergranular attack (inches)
		F temp/ immersion	
FT-ST Poly 1.5 c.	Al	70 total	None observed
1.5 u.	Al	70 total	None observed
66	Al	70 total	Intergranular attack 0.0034 body long.; 0.020 edge trans.
	Al	120 total	None observed
	Al	70 partial	Intergranular attack 0.0191 edge attack
	Al	120 partial	Intergranular attack 0.0191 edge trans. panel
	Mg	70 total	Intergranular attack 0.0116 body; 0.0102 edge
	Mg	120 total	Intergranular attack 0.0032 body, 0.0020 edge
	[illegible]	[illegible]	Intergranular attack 0.0068 body; 0.0088 edge
	Mg	120 partial	No intergranular attack; general surface attack - 0.0032
Fire-Kill II 1.0	Al	70 total	None observed
	Al	70 total	None observed
	Al	120 total	None observed
	Al	70 partial	None observed
	Al	120 partial	None observed
	Mg	70 total	Intergranular attack- 0.0040 body; 0.0044 edge
	Mg	120 total	Intergranular attack 0.0022 body; 0.0036 edge
	Mg	70 partial	Intergranular attack 0.0028 body; 0.0034 edge
	Mg	120 partial	Intergranular attack 0.0028 body; 0.0038 edge
Fire-Kill I 1.0	Al	70 total	None observed

It is recommended that efforts be initiated to develop corrosion inhibitors for short-term retardants or to develop new formulations that will meet established corrosion requirements. Formulations that caused intergranular corrosion on aluminum should not be applied from fixed-wing aircraft, and formulations causing intergranular corrosion on magnesium should not be applied from helicopters utilizing fixed tanks (or other systems where released retardant contaminates the aircraft).

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Aluminum, brass, iron, and magnesium alloys were totally and partially immersed in short-term forest fire retardant solutions at 70° and 120° F, and then examined after 90 days for uniform and intergranular corrosion. Short-term retardants generally caused less uniform corrosion but more intergranular corrosion than long-term retardants, particularly to magnesium. New inhibitor packages should be developed. Two of the formulations tested were recommended for use from fixed-wing aircraft; however, due to severe magnesium corrosion none should be used from helicopters using fixed tank delivery systems.

KEYWORDS: corrosivity, fire retardants, short-term, long-term, procedures, exposure, uniform corrosion, intergranular corrosion, inhibitors, fixed-wing, helicopters, aircraft, alloys

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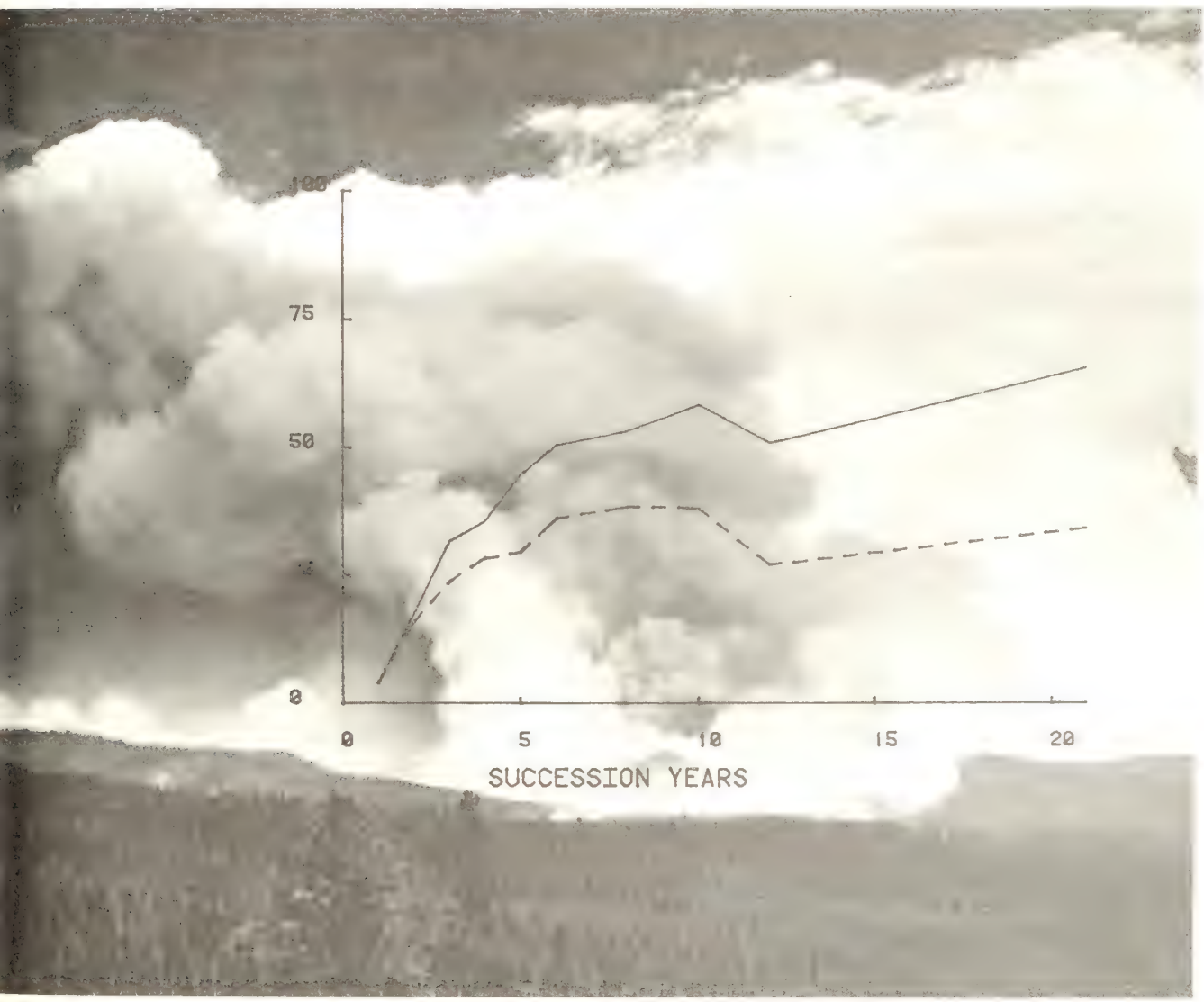
The Sleeping Child Burn—21 Years of Postfire Change

L. Jack Lyon



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RESEARCH SUMMARY

For 21 years following the Sleeping Child Burn of 1961, vegetation development was periodically recorded on 11 permanent transects. Several cultural activities, including salvage logging, cattle grazing, and timber stand improvement thinning, influenced forest community development over short periods, but over a longer time we recorded a surprising stability and resilience in this lodgepole pine forest. Despite major modifications in plant community structure, it i possible to describe a consistent postfire successional pattern.

Long-term attrition of tree seedlings suggests a consistent progression toward 5,000 to 6,000 stems per acre (12 400 to 14 800 stems/ha) in about 30 years from any initial density between 5,000 and 160,000 pe acre (12 400 and 395 000 stems/ha). Dominance appears to be established by the end of the first decade but suppressed trees are extremely persistent.

Shrub communities in these lodgepole pine forests are relatively depauperate and slow to develop. Substantial deviations from a natural growth pattern were recorded as a result of cultural activities, but even in the absence of disturbance it requires at leas a decade for the majority of shrubs to reach mature size.

Vascular cover of native herbaceous species increased from 1 to 2 percent in the first postfire year t 15 percent in the third year and 20 to 25 percent in th sixth growing season. Aerial seeding doubled these percentages, but actual cover values for the first two postfire years were still extremely low.

Snags in the Sleeping Child Burn fell at an annual attrition rate of 10 to 14 percent over 21 years, but rates were much higher for small stems, and the 7 percent of snags standing at the end of the study were mostly in diameter classes greater than 8 inche (20 cm).

A graphic model of postfire forest community development is presented. Within the restrictions imposed by subjective interpretation of available data, this model allows prediction of postfire tree seedling densities and long-term estimates of tree densities, shrub volumes, ground cover percentages, and snag densities.

The Sleeping Child Burn—21 Years of Postfire Change

L. Jack Lyon

INTRODUCTION

In early August 1961, more than 26,000 acres (10 500 ha) of upper montane and subalpine forest on the Bitterroot National Forest burned in a lightning-caused wildfire. At the time, the Sleeping Child Burn represented the single largest forest fire in the Northern Rocky Mountains in more than 20 years. Historically, large wildfires have not been uncommon in this region; but after two decades of successful forest fire suppression, the Sleeping Child was treated as an event almost without precedent. Not only was reseeding and rehabilitation an immediate concern, a substantial effort was invested in attempting to return the burned area to timber production. The burned area also provided an unusual opportunity to evaluate and describe vegetation recovery following a large and intense forest fire.

During the summer of 1962, we established 11 permanent transects designed to sample changes in vegetation structure and development. These transects were sampled annually through 1967 and in alternate years through 1973. At the end of 12 growing seasons, only two of the original transects had not been compromised in some degree by salvage logging, herbicide treatments, post or pole sales, road construction, or cattle grazing. Thus, when the first 12 years of postfire vegetation development were reported (Lyon 1976), the collected information did not represent undisturbed postfire forest succession. Nevertheless, and despite some fairly substantial short-term modifications, the data did demonstrate a vegetation development pattern showing recovery, relative stability, and the substantial resilience of these high-altitude forest communities.

By 1982, vegetation on the Sleeping Child Burn had completed 21 growing seasons. A young and vigorous lodgepole pine forest had replaced the herbaceous community that characterized the burned area during the first decade. Management activities to restore the area as a productive forest had continued, and in many areas the trees had been mechanically thinned. Many snags fell, and in some areas near the road the larger snags were removed for firewood. Although it is not possible to report undisturbed postfire successional development, the Sleeping Child Burn still provides an exceptional opportunity to examine changes in forest vegetation over time. With the passage of 21 growing seasons, the data also provide a tentative model of forest succession and an evaluation of the deviations from normality due to management related perturbations. I am indebted to Peter F. Stickney for the many hours spent recording vegetation data on hot, dry hillsides.

METHODS

Transects to sample vegetation in the Sleeping Child study consisted of 10 circular plots, 23.55 ft in radius (0.04 acre or 0.016 ha), with a paired 2- by 2-ft (0.6- by 0.6-m) plot located 10 ft (3 m) uphill from the circular plot center. Plot centers were spaced at 50-ft (15-m) intervals, and all plots were permanently marked with 3/8-inch (1-cm) steel pins. Most of these steel pins were still intact in 1982, and all data were taken at the same points originally sampled.

Circular Plots (0.04 Acre)

Vegetation sampling in the circular plots through 1973 included counts of all trees and shrubs over 6 inches (15 cm) tall and height and diameter measurements of up to 10 shrubs, by species, in each plot. In 1982, this sample was limited to measurement of all trees and shrubs over 18 inches (46 cm). In addition, the plot radius for trees was reduced to 16.65 ft (0.02 acre or 0.008 ha) to speed field sampling. Trees were classified as over 18 inches, over 4.5 ft (1.4 m), and over 8 ft (2.4 m) in height as a means of separating dominance classes. While fairly large numbers of trees under 18 inches appeared to be present on some transects, I assumed that these individuals were unlikely to have any impact on future development of the burned area. Shrubs were measured on two dimensions of the plant crown (a, b) and height (h). These data were converted to crown volume ($V = \pi abh/4$) to represent the space occupied by shrub crowns.

Two- by Two-Foot Plots

Data recorded in the 2- by 2-ft plots included all vegetation under 18 inches in height to the nearest quarter plot and frequency of occurrence for all plant species. Plant species not contributing a full quarter of cover were combined in a single category.

Summaries

In summarizing data, tree densities are expressed as numbers of stems per acre (stems/ha), shrub volume as ft^3 per acre (m^3/ha), and ground level cover as a percentage. As an aid to visualizing shrub terminology, we found that shrub volumes less than 2,500 ft^3 per acre (170 m^3/ha), unless concentrated in a few large alders or willows, do not produce an impression that shrubs represent a substantial component of the vegetation. If all shrub species are small, like vaccinium and spiraea, shrub volume must exceed 5,000 ft^3 per acre (350 m^3/ha) before producing a visual impression of shrub presence.

MANAGEMENT ACTIVITIES AND TREATMENTS

From 1962 to 1982, but particularly in the years before 1970, the Darby and Sula Ranger Districts conducted watershed rehabilitation, timber salvage, and timber stand improvement (thinning) programs in the Sleeping Child Burn area. Some Christmas tree sales, pole and firewood sales, and a mistletoe control project were carried out; and 400 to 900 cattle were grazed within the burned area each year. Two of these activities appeared to have a potential for producing long-term modification of forest communities in the burn. First, during the initial growing season, the entire burn was treated with an aerial seeding of domestic grasses and forbs. In addition, from 1966 to 1969, much of the burn was treated to prevent the spread of mistletoe, and a number of chemical thinning projects were conducted. Nearly 3,000 acres were treated directly, and a much larger area was affected by drifting herbicides from the treated areas.

In 1976, for the sample transects, direct crown kill amounted to about 623 ft^3 per acre (44 m^3/ha) of shrubs and 11 to 25 percent of the vascular cover on areas treated with herbicides. At the same time, and despite treatments that substantially reduced all forms of vegetation, even the most extreme deviation caused by the treatments was within the range of normal variation for the communities studied.

From 1973 through the end of this study, the Bitterroot National Forest conducted timber stand improvement programs on much of the burned area. In addition to the 10- to 14-ft (3- to 4.3-m) plantation spacing commonly used in this region, several areas were treated with an experimental "crop tree" thinning in which a circular plot was removed around a dominant tree. In many areas, snags were removed in deadwood sales for the house-log market. Cattle grazing continued within the burn, but the available forage resource declined and the number of cattle was reduced to less than 100. Many of the salvage logging roads of the 1960's were closed, but the Sleeping Child Burn remained a popular firewood gathering area for the residents of the Bitterroot Valley.

Toward the end of the study period, big game use of the area increased substantially, and both mule deer and elk were seen in the burned area.

Of the 11 transects established in this study, only one remained essentially undisturbed during the 21 years. Two additional transects were disturbed in only minor ways during the first 12 years and remained undisturbed after that time. Of the remaining eight transects, one was undisturbed until a deadwood sale (1980 to 1981); four others were influenced by aerial herbicide applications (1966 to 1969), but have since remained undisturbed; and three that were treated with herbicides (1966 to 1969) have since been thinned by mechanical means for timber stand improvement. Table 1 presents a brief summary of the disturbances and treatments influencing vegetation development on each of the transects during the two study periods: 1962 to 1973 and 1974 to 1982.

Table 1.—Disturbance and treatment summary for 11 Sleeping Child transects

Transect	1962 to 1973	1974 to 1982
SC01	No disturbance	No disturbance
SC02	No disturbance	Deadwood sale
SC04	Herbicide treatment	No disturbance
SC05	Herbicides, pole sale, cattle grazing	Thinning (crop-tree)
SC06	Herbicides, pole sale, cattle grazing	No disturbance
SC07	Herbicides, pole sale, cattle grazing	Thinning (crop-tree)
SC08	Herbicides, cattle	Thinning (plantation)
SC09	Herbicide drift, cattle	No disturbance
SC10	Herbicide drift	No disturbance
SC11	Herbicide treatment	No disturbance
SC12	Herbicide treatment	No disturbance

POSTFIRE VEGETATION DEVELOPMENT

The variety and combination of treatments received by different vegetation sampling transects in this study has virtually eliminated the use of statistics other than a few undemanding nonparametric tests. The treatments also made it difficult to determine habitat types for the burned-over plots. Keys to habitat type (Pfister and others 1977) are based on the presence of indicator species which, in this study, were invariably poorly represented and in many cases could have been influenced by the treatments. Habitat types represented in the 11-transect sample probably include *Abies lasiocarpa/Vaccinium scoparium* above 7,000 ft (2 100 m) and *Pseudotsuga menziesii/Vaccinium globulare* or *Pseudotsuga menziesii/Calamagrostis rubescens* on different aspects below that elevation.

In general, I have attempted to evaluate relationships demonstrated by the Spearman rank order correlation statistic, or to compare means of three or four transects receiving similar treatment. For some evaluations, transect SC01 has been deleted. This transect was on a severely burned north aspect at 7,200 ft (2 200 m). In several respects it cannot be considered representative of the burned area. Tree densities on SC01 were far lower than those on any other transect and, unlike all other transects, only 36 percent of the trees were lodgepole pine. Only one other transect had less than 90 percent lodgepole in the tree component.

By 1973 natural attrition of lodgepole pine was occurring at about the same rate produced by chemical treatments, and most of the shrub crown losses had been recovered. Vegetal cover had stabilized on most transects even though community structure had been substantially modified in some cases. In 1982 the Sleeping Child Burn gave the casual observer a general impression of a nearly homogenous lodgepole pine forest, but there were still vast differences among transects. Figure 1 shows representative photographs from three of the 11 transects studied.

Figure 1.—Representative photographic display of three transects.

Figure 1.—(con.)

Figure 1.—(con.)

Changes in Tree Density and Dominance

In the initial years after the wildfire, tree seedling densities were as high as 159,000 per acre (393 000/ha) on some transects. The average for all 11 transects was over 34,000 per acre (84 000/ha). Annual attrition of tree seedlings from 1962 to 1973 was 5.77 percent, leading to a survival of 52 percent. Thus, while nearly half of the seedlings died during the first 12 years of study, the average density was still 17,700 live trees per acre (43 700/ha) in 1973. Of these, about 30 percent, or 5,350 per acre (13 200/ha), were over 18 inches (46 cm) tall and were considered likely to be the eventual dominant individuals. The Spearman rank order correlation between initial seedling density and surviving tree density was $r_s = 0.92$, and the correlation between initial density and percentage of survivors over 18 inches was $r_s = -0.90$. For the first 12 years, trees apparently survived in proportion to seedling densities but achieved dominance in inverse proportion to densities.

In 1982, live trees under 18 inches in height were not counted, but the number over 18 inches had only increased to 5,970 per acre (14 750/ha). Because 17,700 live trees per acre (43 700/ha) were present on these sites in 1973, the annual increment to dominance represents a conversion of less than half of 1 percent annually. Small trees that did not achieve dominance in this period will eventually succumb, but their tenacity is indicated by a Spearman rank correlation of $r_s = 0.85$ between seedling density in 1962 and tree density in 1982. Concurrently, there was a strong negative correlation between initial seedling densities and the percent of surviving trees over 8 ft (2.4 m) in height ($r_s = -0.65$). After 21 years, and in spite of some considerable management effort to modify the natural course of forest succession in these stands, trees were still surviving in proportion to immediate postfire densities, while the proportion of dominant trees was in inverse proportion to the level of competition.

Presumably, it will be a number of years before the remaining nondominant trees actually die, but by 1982 it was apparent that these repressed individuals represented little potential for increasing tree densities in the future. In the following discussions, I have assumed that small trees not measured in 1982 will have died by 1991. Thus, the calculated attrition rates and survival estimates presented here (5.9 percent annual loss and 34 percent surviving) are representative of probable tree densities to at least the end of the third decade.

In 1976 I reported that tree seedling attrition and survival on the four undisturbed transects (5.3 percent annually to 55 percent) were not significantly different from attrition and survival on the seven disturbed transects (5.8 percent annually to 52 percent). After 1973, however, only 14 percent of the trees on the undisturbed transects died, compared to 72 percent on the disturbed transects. Comparative annual attrition rates in the two groups were 0.8 percent and 6.9 percent. Potential explanations of the greater attrition rates on the disturbed transects include the possibility of a latent disturbance effect or herbicide influence. More likely, however, direct competition, as determined by tree densities, was responsible. More than five times as many tree seedlings were present on the seven disturbed transects in 1973, and I expected that reduced survival might be detected where competition was high. Disregarding all cultural treatments, for four transects with less than 10,000 initial seedlings per acre (24 700/ha), survival to 1982 was 36 percent, as compared to 31 percent on three transects with an average initial density of 22,000 per acre (54 400/ha), and only 18 percent on three transects with initial densities of 50,000 or more per acre (123 600/ha). On three areas treated with herbicides during the 1960's, attrition was 6.7 percent and survival 46 percent to 1973; but when these same areas were mechanically thinned, annual attrition increased to 16 percent and survival dropped to 20 percent from 1973 to 1982.

Among surviving trees, dominance was clearly established by about the 10th year of growth. The average number of trees per acre over 18 inches (46 cm) tall did not increase substantially in the second decade, and these trees probably represent most of the potential for eventual success. In 1982, only one transect had more than 1,000 trees per acre taller than 8 ft (2.4 m), and no transect had more than 8,500 trees per acre (21 000/ha) taller than 4.5 ft (1.4 m). At all densities greater than 6,000 per acre (14 800/ha), trees over 8 ft in height made up 4 to 9 percent of the population (average 6.3 percent). Below 6,000 trees per acre, the percentage of trees over 8 ft in 1982 was an exponential function roughly expressed: percent $> 8 = 6.3 + 2.2(6-D)^2$, where D = thousands of trees per acre.

Succession model.—If both the mechanical thinning and chemical influences are recognized, these data suggest an outline of a model for lodgepole pine seedling attrition and survival over a period of three decades. With initial seedling densities less than 10,000 per acre (24 700/ha), attrition will be a constant 3.5 percent for the total period. Survival to 30 years should be nearly 50 percent of initial densities.

For somewhat higher initial seedling densities, ranging up to about 25,000 per acre (61 800/ha), attrition will average 6 percent annually for the first decade and drop to less than 3 percent for the remainder of the period. Within this range, survival to 30 years should be 30 to 50 percent of the initial density.

With even higher initial densities, averaging 95,000 seedlings per acre, attrition in the first decade will be 6 percent. But as trees become larger the rate will rise to 7.5 percent for the second and third postfire decades. Survival to 30 years should be only 15 to 20 percent of initial densities.

In the absence of a better model, lodgepole pine forests on the Bitterroot National Forest will normally have 3,500 to 8,000 dominant stems per acre (8 650 to 19 800/ha) at the end of the second decade, and these trees will eventually stabilize at a density no higher than 5,000 to 6,000 stems per acre (12 400 to 14 800/ha).

Development of the Shrub Community

In discussing a forest community as depauperate of shrubs as the Sleeping Child Burn, it is difficult to assign much significance to changes in shrub volumes.

In 1973 only two of the 11 transects had shrub volumes approaching 5,000 ft^3 per acre (350 m^3/ha) and the average for all 11 Sleeping Child transects was 2,077 ft^3 per acre (145 m^3/ha). By 1982 three transects had shrub volumes over 5,000 ft^3, two transects were near 3,500 ft^3 (240 m^3/ha), and the overall average had nearly doubled to 3,983 ft^3 per acre (279 m^3/ha). While this increase appeared to be fairly substantial, it actually represented almost no change in the appearance of the Sleeping Child Burn. In 1973 over 50 percent of all shrub volume was recorded on a single transect, and in 1982 nearly 50 percent was recorded on only two transects. On the remaining nine transects the average shrub volume was 2,491 ft^3 per acre (174 m^3/ha); and on three of these transects, shrubs occupied 1,000 ft^3 per acre or less (70 m^3/ha).

Changes in shrub volume on individual transects between 1973 and 1982, illustrated in figure 2, were quite variable. Three transects demonstrated no change, three increased 100 to 200 percent, four increased 300 to 400 percent, and one had an increase in volume of over 1,000 percent. On the three transects with the majority of shrub volume (63 percent), the average increase was 54 percent between 1973 and 1982. On the eight remaining transects, the average crown volume for shrubs increased by about 230 percent in the same period. However, even though we recorded proportionately greater increases where initial volumes were low, the average volume in 1982 reached only 2,038 ft^3 per acre (143 m^3/ha) on these transects.

In my earlier paper (Lyon 1976), I indicated that additional shrub volumes of 623 ft^3 per acre (43 m^3/ha) would probably have developed on the seven transects treated with herbicides. By 1973, indications were that most of this shrub crown loss would eventually be recovered through regrowth, but almost no evidence indicated that any of the dominant shrub species had been permanently removed from the forest community.

The 1982 comparison of seven chemically disturbed transects with four undisturbed transects shows an increase in shrub volumes of 84 percent versus 178 percent. However, only one of the undisturbed transects had more than 1,100 ft^3 per acre (80 m^3/ha) of shrub volume, and other evidence suggests little likelihood that herbicide treatments had much influence on the differences in shrub volumes. Among the seven treated transects, four remained undisturbed after chemical treatments in 1969. On these transects, shrub volumes increased 63 percent. The remaining three transects were thinned mechanically between 1973 and 1982, and shrub volumes increased by 260 percent.

Shrub responses on the three thinning areas somewhat obscured the potential for evaluating competition between trees and shrubs, but if thinned areas are deleted from analysis, the three areas with the greatest tree densities in both 1973 and 1982 produced shrub volume increases only 50 percent as great as increases on four areas with lesser tree densities.

On the other hand, the Spearman rank correlation between tree densities in 1973 and shrub volumes in 1982

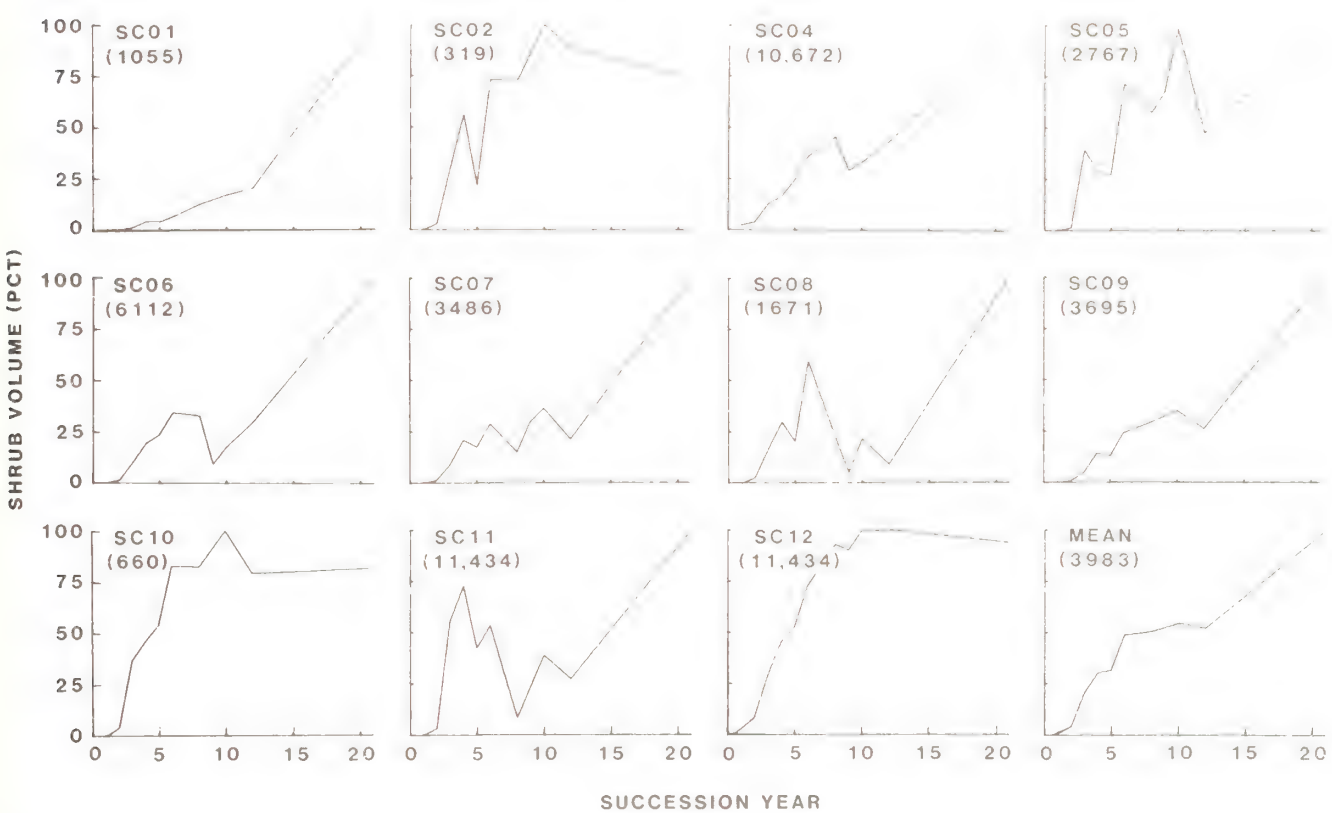


Figure 2.—Shrub volumes on individual transects.

was $r_s = 0.47$, and the correlation between 1982 tree densities and shrub volumes was $r_s = 0.41$. Because both these coefficients are positive, it appears that direct competition between trees and shrubs may not be particularly significant in determining the structure of these plant communities.

Species performance.—In attempting to develop a predictive model for changes in shrub volumes over time, it was necessary to examine the performance of individual species rather than communities on transects. Growth patterns described by transect totals from 1966 to 1969 are relatively erratic (see fig. 2) for a number of reasons. Several of the 16 shrub species[1] identified during this study were susceptible to chemical treatments while others remained almost unaffected. On transects, relatively minor changes in the volume of a few large shrubs obscured any changes in smaller plants, and precipitation in April caused substantial year-to-year differences in average sizes of at least two small-shrub species (Lyon 1976).

Of the shrub species detected during this study, nine were recorded in sufficient numbers to allow evaluation of year-to-year changes in average size. Of the remaining seven, specimens of SARA, RIVI, RILA, VAMY, and SOSC were found on several transects, but in low numbers; SYOR was recorded on one transect until killed by herbicide sprays in 1969; VASC, where present, was almost always too small to be counted under the 6-inch (15.2-cm) height limitation.

For two species, ALSI and LOUT, fewer than 10 specimens were encountered, but the same plants were involved in all measurements. Sample sizes for the other species range from under 50 plants of AMAL each year to 50 to 150 annually for ROGY, SASC, SHCA, and MEFE, and 300 to 400 for SPBE and VAGL.

Examined in the raw data (fig. 3), year-to-year performance of individual shrub species generally confirms the erratic performance on transects. Six of the nine species (ALSI, SASC, LOUT, MEFE, ROGY, AMAL) demonstrated sharp declines in average size at some time between 1966 and 1969. ALSI and LOUT appeared to recover from the chemical spray effects in a single growing season, but the other species remained depressed for several years, and ROGY may never have recovered. If responses to herbicides by SHCA, SPBE, or VAGL occurred, it is not clearly demonstrated in these data as a deviation greater than the normal variation around a generally increasing average.

Succession model.—In attempting to describe undisturbed growth patterns for these nine shrub species, I have assumed that the greatest average size attained during 21 years is probably representative of the size that would have been reached in the absence of mechanical or chemical disturbance. I have further assumed that patterns of growth established before 1966 are descriptively normal, and that any negative deviation recorded between 1966 and 1969 would probably not have occurred in the absence of treatments. Given these assumptions, the predicted growth forms for nin common woody shrubs of the Sleeping Child Burn are are presented in figure 4 as a percentage of maximum size attained.

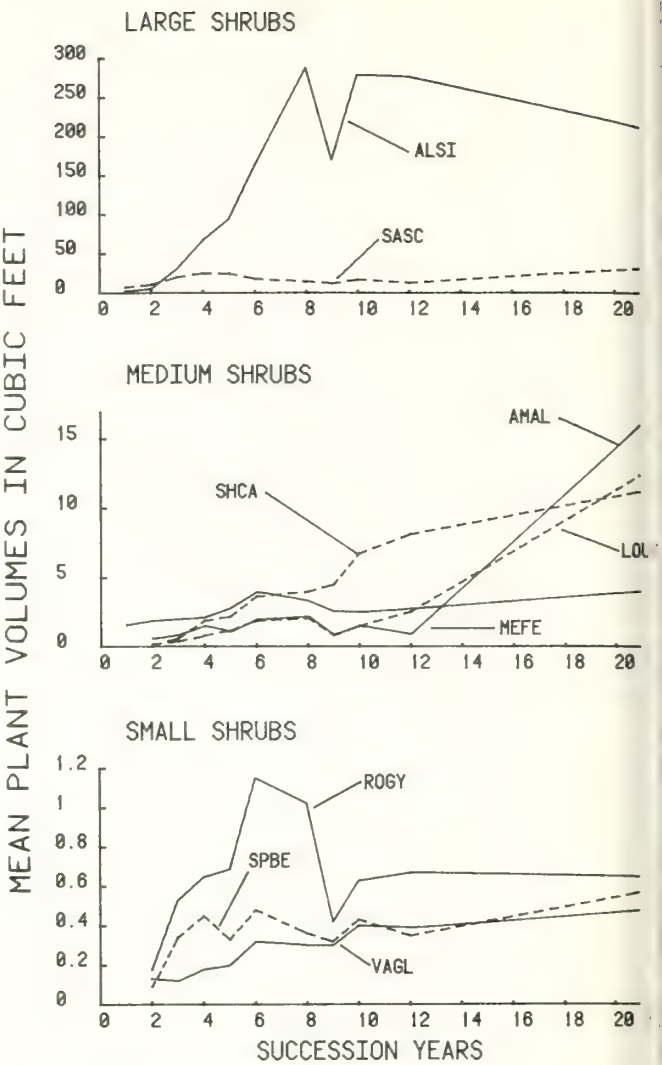


Figure 3.—Performance of nine individual shrub species.

Data points in figure 4 do not provide a good demonstration of the real differences in representative shrub sizes. VAGL, with 0.48 ft^3 per plant (0.013 m^3/plant), was the smallest of the nine species represented here; ALSI was the largest at 289 ft^3 (8 m^3 SASC, which is often considered a large shrub, was ne ly an order of magnitude smaller than ALSI, and none of the other species examined averaged even half the volume of an average SASC.

Despite these substantial differences in individual plant sizes, the nine shrub species in figure 4 appear t describe only a few general patterns of growth over time. SASC and MEFE both recovered crown volume root crowns that were apparently undamaged by fire. For these two species, over 25 percent of eventual cro volume developed in the first postfire growing season, and more than 50 percent was attained in the first 3 years.

[1]In the discussions of this section, I have used the four-letter species designations for shrubs. Each name consists of the first two letters of the genus and the first two letters of the species. The appendix is a summary list of all species mentioned in the Sleeping Child Burn studies.

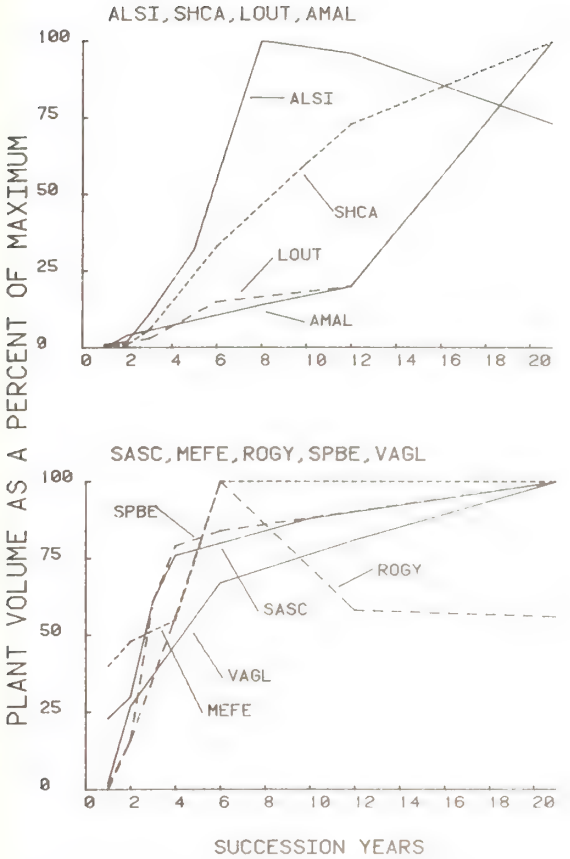


Figure 4.—All shrub species as a percentage of maximum reached.

A similar pattern was seen in ROGY, SPBE, and VAGL, except that initial growth was delayed until the second growing season and 50 percent volume was not reached until 3 to 5 years had passed. The growth curve for SPBE, however, is steeper than the curves for ROGY and VAGL. Of these three species, only ROGY resprouts from a root crown. The others have rhizomes and resprout from any unburned node.

ALSI and SHCA, although both resprout from root crowns, demonstrated a third and even more delayed growth pattern in which 4 to 5 years were required for 25 percent of eventual crown size to be attained. After the fifth growing season, ALSI expanded far more quickly than SHCA and then declined in size through the second decade. Unfortunately, this particular part of the growth curve is within the period of chemical applications, and the described pattern might reflect the response to herbicides.

Finally, LOUT and AMAL demonstrated a slow development pattern in which less than 25 percent of eventual volume was attained during the first decade. This same slow rate of increase was continued through the second decade. The effects of herbicide applications could be involved in this pattern, but the sample sizes, especially for LOUT, are small; and it was possible to evaluate the performance of specific plants to confirm that the pattern is consistent on transects where there was no exposure to herbicides.

Vegetal Cover

From 1973 to 1982, average vegetal cover at ground level increased from 51 to 66 percent on the 11 sample transects (table 2). This apparent 15 percent increase is deceptive, however, because over half the increase was in moss and lichen cover; and there was only one transect on which vascular cover was greater than had already been recorded some time prior to 1973. With minor exceptions, the graphic presentations in figure 5 suggest that development of vascular cover may have stabilized after about the sixth postfire growing season. Vascular cover declined by 7 percent between 1971 and 1973 as a result of the loss of introduced grasses, but a subsequent increase in native vascular plants was equivalent to this loss, and vascular cover in 1982 was only slightly different from vascular cover in 1967.

In my 1976 report, I attributed some significance to the fact that vascular plants represented 85 percent of total cover on four undisturbed transects, while mosses and lichens contributed over 50 percent of the cover on the remaining, chemically disturbed, transects. From 1973 to 1982, vascular cover increased by an identical 7 percent in these two groups of transects. However, moss and lichen cover increased by more than 20 percent on the undisturbed transects and not at all in the disturbed areas. The result was that by 1982 both groups were nearly 50 percent vascular and close to the

Table 2.—Percentage vegetal cover, average for 11 transects, 1962 to 1982

Source	Year									
	1962	1963	1964	1965	1966	1967	1969	1971	1973	1982
All vegetation under 18 inches	4.1	17.7	31.8	35.7	44.5	50.5	53.2	58.2	50.8	65.7
Vascular vegetation	4.1	16.1	23.9	28.4	29.6	36.1	38.2	38.0	27.1	34.1
Introduced species	2.7	9.0	10.6	12.0	12.6	14.5	13.8	13.3	4.7	.6
Perennial grasses	2.2	8.2	10.4	12.0	12.6	14.5	13.8	13.3	4.7	.6
Annuals	.6	.8	.2	—	—	—	—	—	—	—
Native species	1.4	7.1	13.3	16.4	17.0	21.6	24.4	24.7	22.3	33.7

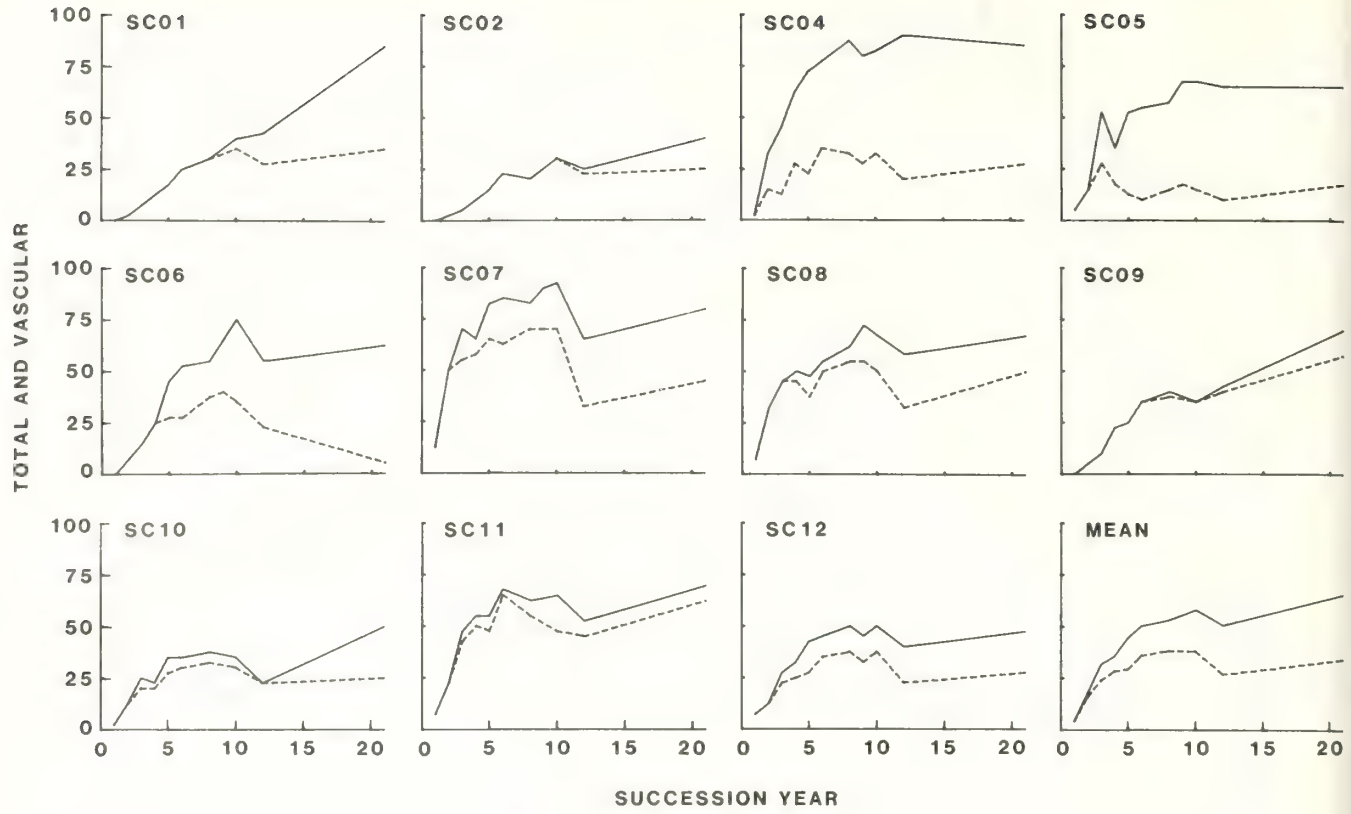


Figure 5.—Herbaceous cover, total and vascular, all transects.

overall average of 34 percent vascular cover. Any structural modification of ground-level vegetation related to herbicides was apparently assimilated in these plant communities.

In examining the data for other possible relationships affecting vegetal cover, I found that a strong influence was apparently exerted by trees. Vascular cover on four transects with fewer than 2,000 trees per acre (4 900/ha) in 1982 was over 50 percent, while seven transects with more than 3,000 trees per acre (7 400/ha) averaged less than 25 percent vascular cover. The Spearman rank correlation between tree density and vascular cover was $r_s = -0.70$, while the correlation between tree density and nonvascular cover was $r_s = 0.53$.

To evaluate the performance of individual species in the ground-cover layer (table 2), I repeated the calculations of 1976 in which all vegetal cover less than one-fourth plot was proportioned among the species present on the basis of plot frequencies. This calculation probably overestimates grass cover and underestimates forbs and small shrubs, but trends are represented consistently. The actual percentages involved are so small that no meaningful error is considered likely. A total of 43 vascular plant species were identified in the sample plots in 1982, but only 20 of these produced more than 0.5 percent cover on at least one transect, and eight of the 20 were found on fewer than five transects. Thus, only a few species could be examined individually for response to disturbances and prediction of growth patterns.

In both 1982 and 1973 VASC was the most ubiquitous plant species in the burn, and the only species other than lodgepole pine detected on every transect. Cover of VASC ranged from 1 to 33 percent and averaged 10 percent on 11 transects. This range is somewhat greater than was recorded in 1973, when every transect had at least 0.7 percent VASC cover and the mean for all transects was 4 percent. One substantial reason for the range of values recorded is seen in the continuing negative response of VASC to virtually any kind of vegetation manipulation. In 1973 four undisturbed transects had 10 percent VASC cover, while seven disturbed areas had only 1 percent. One of these disturbed areas was in a pole sale, and all had been influenced by herbicides. Although VASC cover had doubled by 1982, to 20 percent on the undisturbed areas and 3 percent where disturbed, there is little evidence that cover lost in the disturbances will ever be entirely replaced. Disturbances after 1973 were also calamitous for VASC. Three transects that remained undisturbed for 21 years had 16 percent VASC cover, four transects undisturbed after 1973 had 6 percent VASC cover, and three transects on which timber stand improvement was conducted after 1973 had an average of only 0.3 percent VASC. Only one transect that was ever disturbed has developed more than 6 percent VASC cover, while no undisturbed transect has developed less than 10 percent.

LUSU was detected on eight transects and provided cover in excess of 12 percent on three transects in the period before 1969. Following the herbicide applications LUSU disappeared from two transects and declined from over 3 percent to less than 0.5 percent average cover on all transects. By 1982 LUSU had disappeared from three

more transects and had recovered to only 9 percent on the three transects where it was still present. Clearly, LUSU is a species with virtually no tolerance for herbicides and no capacity to recover from herbicide treatments.

XETE was detected on all 11 transects in 1973, but was only found on eight in 1982. Average cover of XETE for all transects apparently stabilized at 2 to 3 percent at the end of the first postfire decade, and has remained at that level independent of other plant community changes.

CARU was detected on seven transects in 1982. It is an important cover species on five transects, including four where it averaged 12 percent cover in 1973. On the four transects of best development, CARU cover had increased to 19 percent in 1982. Throughout the burn, CARU cover increased from 4 to 8 percent. There is no suggestion in any of the available data that CARU was influenced by any particular factor other than the fact that the four transects on which it reached greatest development are located between 6,700 and 7,000 ft (2 000 and 2 100 m).

EPAN has apparently continued to exist as a more or less sporadic presence throughout the burn area. Contrary to the overwhelming dominance sometimes seen in other forest types (Stickney 1980), EPAN has never been recorded with more than 3 percent cover on any transect in the Sleeping Child Burn. It was recorded on seven of 11 transects in 1982. The best development coincided with the most recent disturbance, but the average EPAN cover for all transects remained fairly consistently around 0.5 percent after about the third postfire growing season.

The three species of carex—CARO, CAGE, and CACO—developed to an average 2 percent cover in the burn in the eighth postfire year, and have remained at that level. CARO was detected on 10 transects in 1982 and is the most widespread of the three species. Carex species reached the greatest development on two easterly aspects where 11 percent and 4 percent cover was recorded in 1982. The data do not suggest that carex development was modified by cultural disturbance.

Only four other vascular species exceeded 0.1 percent cover and were recorded on more than four transects in 1982. All were introduced in the aerial seeding for watershed protection immediately after the fire. Of the six species included in the mixture, two had virtually disappeared by the fourth growing season. SECE and TRRE briefly produced about 1 to 2 percent cover in the early postfire years, but thereafter failed to survive or reproduce.

The more successful species in the seeded mixture were all perennial grasses. Of these, DAGL appeared to be the most successful during the first postfire decade. However, DAGL declined drastically in response to two dry seasons before 1973, and has declined continuously from 9 percent cover in 1967 to 2 percent in 1973 and 0.1 percent in 1982.

FEOV was the second most successful seeded grass during the first decade in that it reached 2 percent cover by the second year and then remained at that level. Although FEOV was still present on 10 of the 11 transects in 1982, it had declined to 0.2 percent cover in the burn. PHPR also produced cover in the 2 to 3 percent range for several years, but dropped below 2 percent in 1966 and continued to decline to 0.7 percent in 1973 and to a trace on five transects in 1982.

Of the seeded perennial grasses, BRIN originally appeared to be the least successful. It never exceeded 1 percent cover and remained below that level during the entire study. However, BRIN is apparently persistent. In 1982 it was still present on six transects and produced 0.3 percent cover.

Species Frequencies

Plant communities in the Sleeping Child Burn are relatively uncomplicated. Even the most complex transects contained fewer than 20 species in the 10 small sample plots. The average transect had 20 vascular species made up of 11 herbaceous plants, seven shrubs, and two trees. Only one transect had more than 25 species, and none exceeded 30. Considering only those species recorded in the small plots, an average nine species were recorded 1 year after the fire, 14 species were recorded in the eighth growing season, 13 in the 12th season, and 15 in year 21.

Excluding trees and shrubs, herbaceous species recorded in the small plots can be combined in six plant groups to provide an illustration of long-term trends. Figure 6 expresses the average combined frequency of occurrence for six plant groups on 11 transects as the probability of finding any representative of the group in a random sample plot. Probability can exceed 1.00 when two or more representatives of the same group are commonly found in plots.

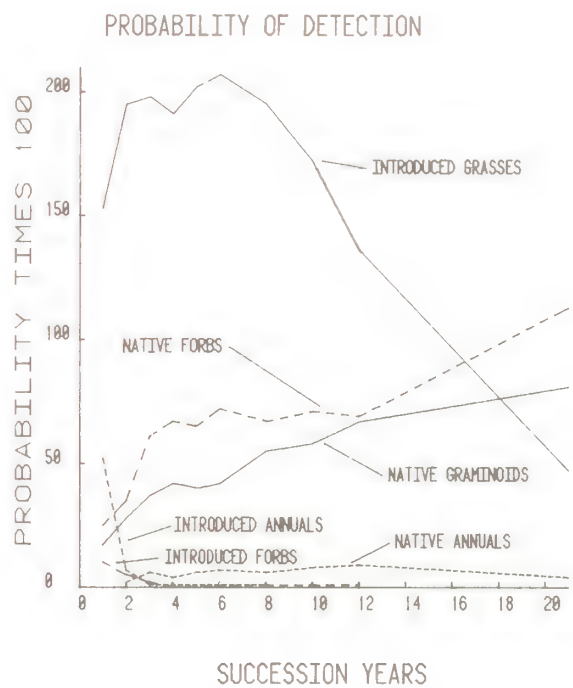


Figure 6.—Probabilities of occurrence in sample plots for six plant groups.

These probability data indicate several significant trends and demonstrate some changes in community composition that were only partially defined after the first 12 postfire years. Trees and shrubs, as well as the plant groups illustrated in figure 6, had nearly stabilized by the fourth growing season. Following stabilization, native graminoids increased at a slow but consistent rate of about 2.4 percent each year. By 1982 they were found in more than 80 percent of the plots. On the other hand, the introduced grasses were found in plots at a probability exceeding 1.00 for more than 12 years, but declined continuously from about the sixth growing season to a probability less than 0.50 in 1982. Although no longer important as cover, these species were still common throughout the burn at the end of the study.

Introduced annuals and forbs both disappeared from the sample plots by the third year and native annuals maintained a low, but relatively consistent, probability below 0.10. Native perennial forbs appeared to have stabilized at about P = 0.70 during the first decade, but over the second decade increased to appear in nearly every plot.

Succession model.—The frequency data illustrate a slow, long-term increase in native forbs and graminoids and confirm the persistence of introduced grasses. All changes are gradual, however, and it appears that herbaceous cover estimates of the fourth postfire succession year will adequately describe trends for at least 20 years in these forest communities.

Ecological Effects of Disturbances

Throughout these presentations of tree, shrub, and vascular cover changes over time, it was apparent that management related disturbance had a substantial influence in the development of forest communities in the Sleeping Child Burn. At the same time, comparisons of disturbed and undisturbed transects suggested that these communities are resilient. In most cases the disturbance produced a diversion from an apparently established path rather than a long-term permanent change. Trees and shrubs, in particular, appeared to recover from the disturbances of the first decade and to reinstate those community structures that might have been expected in the absence of disturbance. At the same time, and despite the relative tolerance of the larger woody species to various kinds of disturbance, some permanent changes occurred in smaller perennials in the ground-cover layer. On a few transects, and particularly as a result of mechanical influences, cover of VASC was reduced below levels recorded prior to disturbance and has remained low. LUSU was also reduced, or completely removed, from every community in which it was detected.

The influence of aerial seeding in the Sleeping Child Burn was also important in the first decade. For at least 10 years, the seeded species contributed significantly to ground-level cover. Competition from seeded species produced some reduction of lodgepole pine seedling densities during the first few postfire years, and seeded species may also have retarded the growth of native vascular plants.

In retrospect, it is hard to attach as much significan to these changes as I did in 1976. The loss of LUSU, because the species is a nitrogen fixer, may be a chang that has ecological significance. Otherwise, at the prec sion level of this study, it is not possible to demonstra any change greater than a short-term replacement of native graminoids by introduced species and a more pe manent substitution in which the less tolerant native vascular species have been replaced by the more tolera native species. Apparently, even relatively simple fores communities could assimilate perturbations of the kind reported here. Possibly as important as the ecological questions are the economic evaluations that would det mine whether manipulations of these forest communiti produced beneficial results in long-term forest management.

DENSITY AND ATTRITION OF SNAGS

In the immediate postfire sampling period, snag densities on the Sleeping Child Burn averaged 497 per acr (1 230/ha). Because the majority of these snags were dead lodgepole pine, some direct correlation was expected between snag density and tree seedling density. However, this did not prove to be true. The three transects with the highest snag densities produced onl medium density tree stands, and the two transects wit the lowest snag densities produced the highest seedling densities. The Spearman rank order statistic for snag density and seedling density was $r_s = 0.10$ for the 11 study transects.

With a sample involving only 11 transects, development of a predictive model for postfire tree seedling densities is speculative. However, the available data strongly suggest that wherever snag densities exceed 200 per acre (500/ha), sites on aspects between azimuth 290° and 45° at elevations between 6,500 and 6,800 ft (2 000 and 2 100 m) are likely to have much higher seedling densities than sites outside that range.

From 1962 to 1976, snags on eight transects remaine undisturbed by other than natural causes. For 2 years, less than 2 percent of these snags fell, but over the ne 13 years, 85 percent fell at an annual attrition rate of 13.4 percent (Lyon 1977). Snags on one transect were removed in a deadwood sale before 1982, but data fron the remaining seven transects indicate the attrition rat had declined to 10.8 percent after 1976, and nearly 93 percent of all snags had fallen in 21 years (table 3 and fig. 7).

An average attrition rate between 10 and 14 percent somewhat misleading because snags under 3 inches (8 cm) went down at a much higher rate than the large stems. After two seasons of less than 1 percent annual loss, attrition of small stems averaged 27.9 percent annually for 13 years and 25.9 percent through the 21st year. Snags 3 to 8 inches (8 to 20 cm) in diameter were slightly more persistent, but fell at a nearly constant rate of 8.4 percent through the 15th year and at 11.1 percent through 1982. Snags larger than 8 inches fell a an annual rate of 8.6 percent through 1976 and 8.3 per cent thereafter. Attrition for these larger snags was

Table 3.—Numbers of snags per acre on sample transects by year of count

Transect	Year						
	1962	1963	1966	1969	1971	1976	1982
SC01	498	498	393	343	333	258	183
SC02	390	383	188	160	123	73	
SC04	423	413	190	145	110	68	20
SC08	240	240	148	83	38	15	10
SC09	693	685	403	268	203	75	25
SC10	918	918	358	160	95	28	5
SC11	570	565	265	170	108	35	3
SC12	243	223	198	160	118	53	23
Average	497	490	268	186	141	75	38

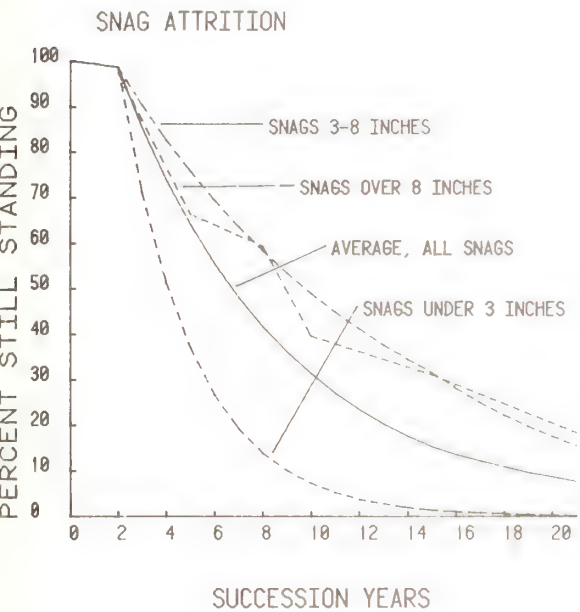


Figure 7.—Percentage of snags still standing, by year and diameter class.

characterized by sporadic blowdown rather than consistent annual losses. Within the small sample of stems over 12 inches (30 cm), the annual attrition rate was only 5.4 percent from 1976 to 1982.

POSTFIRE SUCCESSION MODEL

In this section I have combined all the preceding data summaries and discussions into a model describing postfire vegetation development on the Sleeping Child Burn. The described changes in postfire community structure are based on averages and probabilities derived from the 11 transects, and a considerable subjective judgment concerning the probable course development might have taken in the absence of herbicide treatments, seeding of exotic grasses, and timber stand thinning projects. Where possible, I have indicated a range of values associated with each graph. Although this model could be used in a predictive sense, the assumptions made and the limits of the data base require that it be considered a purely descriptive model for a specific situation and a limited range of habitat conditions.

Tree Densities

Following a crown fire in the mature forest, initial tree seedling densities were expected to be a direct function of lodgepole pine snag densities. However, there was little relationship between snag densities and seedling densities. The best available descriptor, assuming a minimum of 200 lodgepole pine snags per acre (500/ha) as a seed source, suggests that sites on azimuths between 290° and 45° at elevations between 6,500 and 6,800 ft (2 000 and 2 100 m) are likely to have 50,000 or more seedlings per acre (123 600/ha), while other sites below 7,000 ft (2 100 m) will have 10,000 to 20,000 seedlings per acre (24 700 to 49 400/ha), and sites above 7,000 ft less than 5,000 seedlings per acre (12 400/ha) (fig. 8a).

Changes in tree density will show an average attrition of 6 percent annually during the first decade for all initial densities greater than 10,000 per acre (24 700/ha). Where initial densities are no greater than 25,000 per acre (61 800/ha), this rate will drop to 3 percent for 20 additional years. At higher seedling densities, the attrition rate increases to 7.5 percent during the second and third postfire decades. If initial seedling densities are quite low, less than 10,000 per acre (24 700/ha), attrition will be a constant 3.5 percent for three decades, and for some very low initial seedling densities an increase may be recorded (fig. 8b).

In the absence of a better model, I suggest that lodgepole pine forests similar to the Sleeping Child Burn will normally have 3,500 to 8,000 dominant stems per acre (8 700 to 19 800/ha) at the end of the second decade, and that tree densities will eventually stabilize at no more than 5,000 to 6,000 stems per acre (12 400 to 14 800/ha).

Shrubs

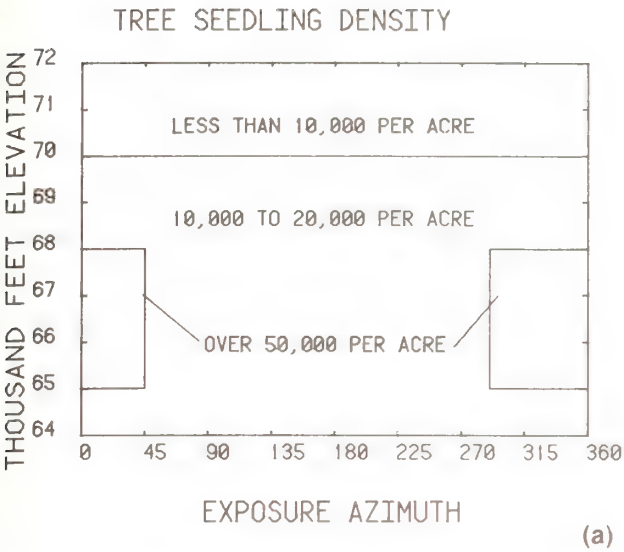
Average shrub volumes leveled off at just over 2,000 ft^3 per acre (140 m^3/ha) between the sixth and eighth postfire years on the Sleeping Child Burn, but it was evident that stabilization occurred as a result of herbicide effects. Even a straight line projection of the growth required to reach nearly 4,000 ft^3 per acre (280 m^3/ha) between years 6 and 21 suggests that the avera at the end of the first decade could have been at least 2,500 ft^3 per acre (175 m^3/ha). An even higher estimate can be derived from the fact that the majority of shrub in these plant communities attained 50 percent of their eventual size in 6 years or less. A curvilinear extension of shrub volume changes after the sixth year suggests that an average as high as 3,000 ft^3 per acre (210 m^3/ha at the end of the first decade would not have been unexpected.

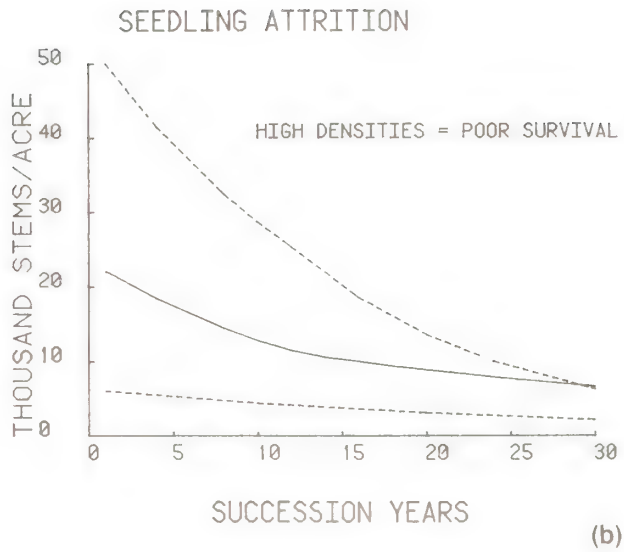
However, any attempt to model shrub volumes on averages will prove somewhat deceiving. For the sampl available in this study, the modal value is one-third lower than the mean; nearly half the transects had shru volumes less than one-half the mean volume. If the 11 sites in this study are representative, over two-thirds o all shrub volume will normally develop on about one-fourth of the area. Mean shrub volumes on the remaining three-fourths will only be slightly greater than half the mean for all areas (fig. 8c).

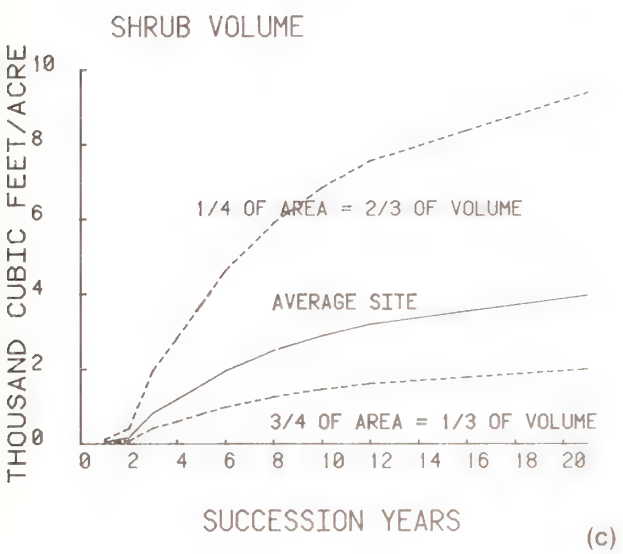
Herbaceous Cover

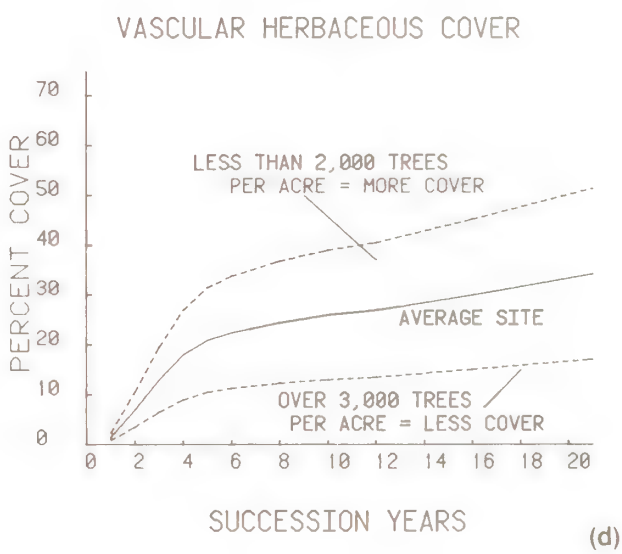
Expressed in a general descriptive model for the Slee ing Child Burn, vascular herbaceous cover increased from 1 to 2 percent in the first postfire year to about 1 percent in year 3 and 20 to 25 percent in year 6. Thereafter, increments averaged less than 1 percent per year. Deviations from this pattern (fig. 8d) were related to tree densities. About 50 percent more vascular cover than average developed where tree densities were below 2,000 per acre (4 900/ha), and 50 percent less cover developed where tree densities exceeded 3,000 per acre (7 400/ha).

Nonvascular mosses and lichens exhibited a much slower rate of growth that did not begin until at least succession year 2 and may not have been important until years 5 and 6. In a generalized model (fig. 8e), development proceeded at a consistent 2 percent per year with 50 percent more nonvascular cover in dense tree stands and 50 percent less where tree densities wer low.









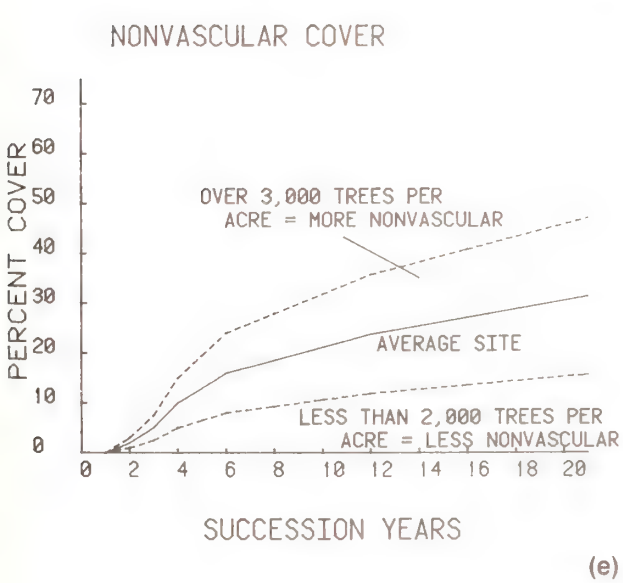


Figure 8.—Forest succession model: (a) tree seedling densities, (b) tree seedling attrition, (c) shrub volumes, (d) herbaceous cover, (e) nonvascular cover.

MANAGEMENT IMPLICATIONS

The succession model presented in this paper has several limitations that could prevent widespread application as a management tool. For example, extrapolation beyond the immediate vicinity of the Sleeping Child Burn clearly involves a substantial potential for error. In addition, similar results could not necessarily be expected for situations where the burned area is small and external seed sources could influence plant community development. However, with care in application, the model may have practical use in situations where lodgepole pine is the primary tree species of a burned area.

Available data proved to be somewhat of a disappointment in providing a method for predicting postfire tree seedling densities, but they do suggest two kinds of problem areas likely to be created by large fires. In areas above 7,000 ft (2 100 m), regeneration will almost certainly be inadequate. In areas below that elevation, tree densities will universally be so dense that some management action will be indicated. Favorable northerly aspects will be particularly troublesome.

In attempting to modify high tree densities, the experiences of the Bitterroot National Forest suggest that achieving acceptable timber management objectives is a more difficult problem than previously recognized. Of the several thinning methods tested in this burn, only direct cutting after about the 10th year seems to have been successful. On some sites, herbicide applications killed large numbers of trees, but none of the chemical treatments reduced tree densities to acceptable levels. While long-term side effects with herbicide treatments may have occurred, this could not be confirmed.

There were, however, some consistent patterns in the development of tree densities that might be helpful. On sites considered overstocked, long-term attrition of seedlings suggested a consistent leveling toward 5,000 to 6,000 stems per acre (12 400 to 14 800/ha) at about 30 years. This density is still far too high, but it was accompanied by establishment of dominance among live trees before the 10th postfire year. Because the number of trees over 18 inches (46 cm) tall did not increase substantially during the second decade, the opportune time to schedule timber stand improvement projects may be the end of the first decade, after dominance has been established.

If the Sleeping Child Burn is typical, only limited opportunity exists for manipulation of shrub communities with fire or as a part of postfire management. Virtually all the shrubs detected in the postburn community were present before the fire, and shrub volumes recorded after the fire were far lower than in unburned stands. Further, only two of the recorded shrub species recovered from burning at a rate commensurate with replacement of preburn volumes in less than 5 years. Among the shrub species expected to be dominant in mature forest communities, none recovered at a rate that would replace preburn volumes in less than a decade. The one response suggesting a potential for positive manipulation of shrubs was the increase in volume of species other than VASC when tree stands were thinned during the second decade. VASC did not respond favorably to disturbance of any kind.

Considering the relative weakness of the shrub component and the ubiquitous occurrence of VASC in these forest communities, the manager may have little apparent reason to attempt manipulation. At best, using prescribed fire as a tool, it may be possible to treat selected sites that are already dominated by shrubs and restore some vigor to existing decadent plants. Timber stand improvement thinnings could also increase shrub volume if such projects are delayed until at least the 10th postfire year. However, some care may be required in evaluating this response because substantial losses in VASC volume will accompany increases in other shrub species.

In the postfire period on a large burn, an immediate management concern is the potential for watershed damage. The Sleeping Child model suggests that, if live vegetation is the only criterion, there is reason for concern and little that can be done to alleviate it. These burned sites are considered vulnerable for at least the first 2 years. Thereafter, native vegetation will provide cover in the 10 to 15 percent range. Rehabilitation by aerial seeding will double ground cover during this early period, but the actual cover values will still be extremely low. During the first postfire growing season in this burn, live ground cover was less than 5 percent, but half of that was supplied by introduced species.

Finally, the model provides the manager a method of predicting rates at which snags will fall. This may be important in scheduling deadwood sales and firewood permits. In general, 25 percent of the usable snags will have fallen in 5 years, and 50 percent will be down in 10 years.

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APPENDIX: PLANT NAME ABBREVIATIONS USED

Trees:

PICO	*Pinus contorta* (lodgepole pine)
PSME	*Pseudotsuga menziesii* (Douglas-fir)

Shrubs:

ALSI	*Alnus sinuata*
AMAL	*Amelanchier alnifolia*
LOUT	*Lonicera utahensis*
LUSU	*Lupinus sulphureus*
MEFE	*Menziesia ferruginea*
RILA	*Ribes lacustre*
RIVI	*Ribes viscosissimum*
ROGY	*Rosa gymnocarpa*
SARA	*Sambucus racemosa*
SASC	*Salix scouleriana*
SHCA	*Shepherdia canadensis*
SOSC	*Sorbus scopulina*
SPBE	*Spiraea betulifolia*
SYOR	*Symphoricarpos oreophilus*
VAGL	*Vaccinium globulare*
VAMY	*Vaccinium myrtillus*
VASC	*Vaccinium scoparium*

Vascular herbaceous:

BRIN	*Bromus inermis*
CACO	*Carex concinnoides*
CAGE	*Carex geyeri*
CARO	*Carex rossii*
CARU	*Calamagrostis rubescens*
DAGL	*Dactylis glomerata*
EPAN	*Epilobium angustifolium*
FEOV	*Festuca ovina* var. *duriuscula*
PHPR	*Phleum pratense*
SECE	*Secale cereale*
TRRE	*Trifolium repens*
XETE	*Xerophyllum tenax*

Lyon, L. Jack. The Sleeping Child Burn—21 years of postfire change. Research Paper INT-330. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1984. 17 p.

For 21 years following the Sleeping Child Burn of 1961, vegetation development was recorded on 11 permanent transects. Several cultural activities, including salvage logging, cattle grazing, and timber stand improvement thinning, influenced forest community development over short periods, but over a longer time we recorded a surprising stability and resilience in this lodgepole pine forest. Despite major modifications in plant community structure, it is possible to describe a consistent postfire successional pattern. A graphic model of postfire forest community development is presented.

KEYWORDS: fire, forest succession, herbicide side effects

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Native Shrubs: Suitability for Revegetating Road Cuts in Northwestern Montana

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RESEARCH SUMMARY

Eighteen species of native shrubs and forbs were planted to evaluate their potential for revegetating road cuts in northern Idaho and western Montana. One-year-old seedlings were planted, both alone and in combination with grasses and legumes, in the Coram Experimental Forest in northwestern Montana. Growth, regeneration, and general condition were observed 9 years after planting.

Survival, averaged over all sites, was very good for some species: Wood's rose (82 percent), red-osier dogwood (94 percent), and thimbleberry (73 percent). Wood's rose, bush penstemon, lovely penstemon, and blackcap grew and regenerated well over the 9-year period (1974 to 1983). Most of the other species planted either died or did not grow and develop well. All species were rated for suitability based on initial survival, final survival, growth, vigor, natural spread, and potential for soil stabilization. Species attributes were listed for the eight highest rated species.

Grasses and legumes provided early surface stabilization while the roots of shrubs developed and provided deeper soil stabilization. Study results indicate that road cuts can be effectively revegetated with native shrubs. Shrub survival was not reduced by grasses and legumes.

Native Shrubs: Suitability for Revegetating Road Cuts in Northwestern Montana

Roger D. Hungerford

INTRODUCTION

Constructing roads to harvest timber or explore for minerals creates problems ranging from slope erosion and stream siltation to loss of scenic value. Revegetation can eliminate or reduce these problems. Many road cuts on National Forests in the Northern Region of the U.S. Department of Agriculture, Forest Service are seeded with grasses and legumes to aid revegetation. Fill banks respond well to this treatment, but harsh sites and cut banks usually remain barren. In these problem areas, planting appropriate shrubs and forbs can accelerate revegetation.

The use of shrubs for revegetation is not new. In the 1930's Juhren successfully used them for soil stabilization on slopes in California (Gallup 1974). Plummer (1970) reported on plants for revegetating road cuts in the Intermountain area (Utah, Nevada, and southern Idaho). Several species of shrubs have been tested for revegetating winter game ranges in southwestern Idaho (Holmgren 1954; Medin and Ferguson 1980). Plummer and others (1968) also used shrubs to restore big game habitat in Utah.

The purpose of this study was to evaluate the use of shrubs and forbs native to northern Idaho and western Montana for revegetation along western Montana road cuts. Eighteen species were chosen based on previous research results and each plant's potential for soil stabilization, availability, and survivability. The primary objective was to evaluate survival capability and soil stabilization potential of the planted shrubs and forbs on road cuts. A second objective was to evaluate shrubs and forbs together with a locally used grass and legume seeding mixture for revegetation effectiveness. Survival data 4 years after planting are presented and effectiveness for site stabilization is discussed by species. Interactions between shrubs and forbs and grasses and legumes are discussed.

STUDY AREA

An effort was made to conduct the study in representative areas along forest roads. Test sites were located on the Coram Experimental Forest (fig.1) along two logging roads: a new road and a 20-year-old road with unvegetated cut slopes. Douglas-fir/ninebark (*Pseudotsuga menziesii/Physocarpus malvaceus*) and subalpine fir queencup beadlily (*Abies lasiocarpa/Clintonia uniflora*) habitat types are predominant in the study area. The area ranges in elevation from 4,200 to 5,200 feet (1 280 to 1 585 m) and receives an average of 33 inches (84 cm) of precipitation annually.

Approximately 3,700 feet (1 128 m) of road cuts were selected for planting on south, east, and west slopes. Cut bank slopes of ¾:1, 1¼:1, and a terraced cut through fractured rock were planted. Slope distances (from road to top of cut) varied from 10 to 70 feet (3 to 21 m). Soils along the cut banks are weathered limestone and calcareous argillites, with a pH of 7.0 to 8.0 (Klages and others 1976). Subsoils (from the B and C horizons) and fractured rock range in depth from 0 to 4 feet (0 to 1.2 m) below the undisturbed surface. Soil structure varies from weak, fine, subangular blocky to massive, with 20 to 80 percent rock. Soil texture varies from gravelly, silty clay loam to gravelly silt loam. The soils in the study area are characterized by a low organic content (0.6 to 1.4 percent) and a cation exchange capacity (CEC) of 8.2 to 19.6 meq/100 g. Soils contain from 0.03 to 0.07 percent total nitrogen and 3.8 to 28.0 ppm available phosphorus.

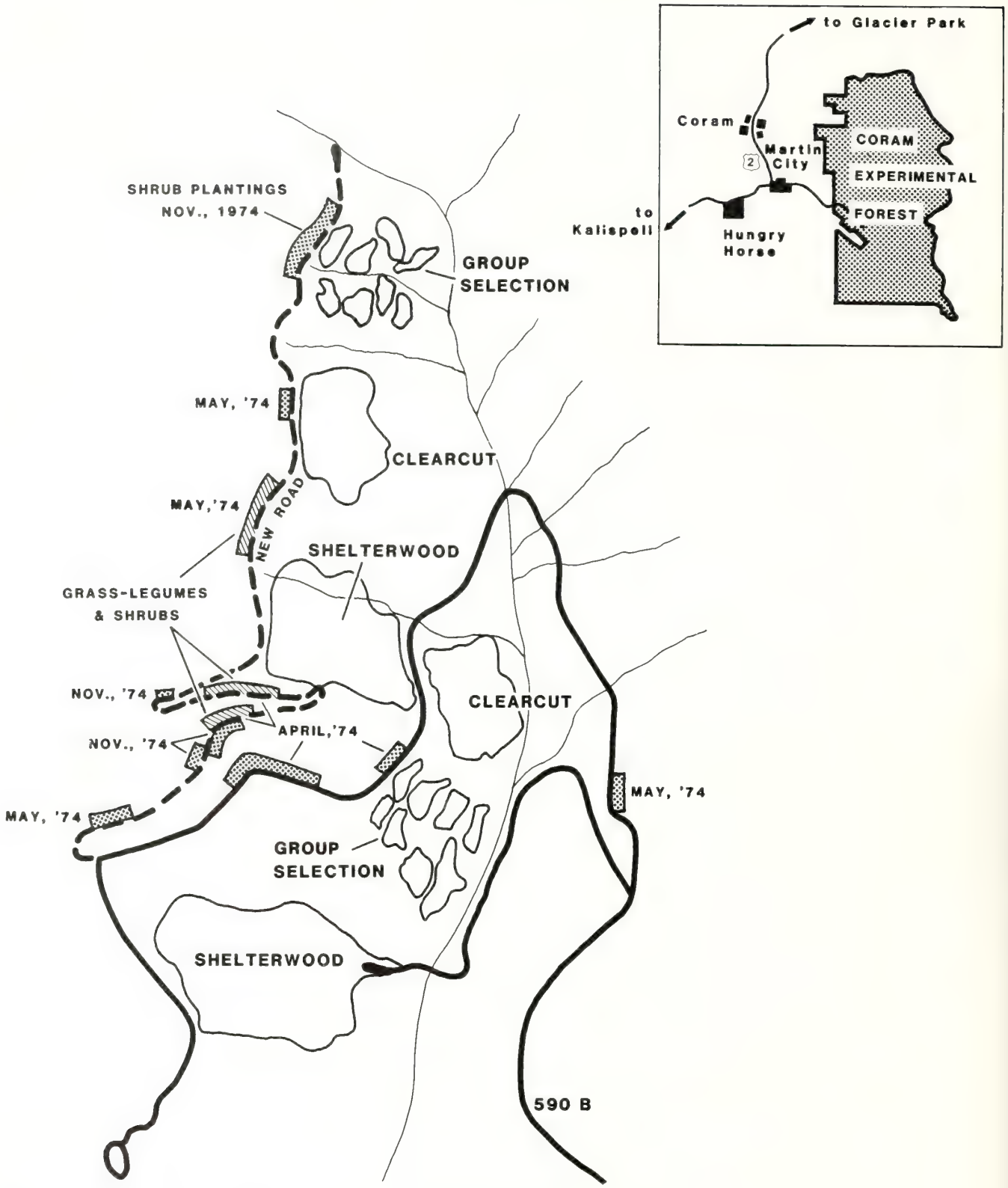

Figure 1.—Location of shrub planting sites on the Coram Experimental Forest, showing the new road and old road. Location of grass and legume plantings is shown.

METHODS

Shrubs and Forbs

Information about shrub species and their effectiveness in revegetation was obtained from published sources (Plummer and others 1968; Plummer 1970), the field experience of Monsen (at the Intermountain Station's Forestry Sciences Laboratory in Boise, Idaho) and Jensen (at Montana State University in Bozeman, Mont.), and the results of plantings on the Colville and Coeur d'Alene National Forests (Mason and others 1973). From this information, a list of species suitable for planting study sites was compiled, based on species' adaptability and their potential for soil stabilization. The 18 species of shrubs planted in the study areas (appendix 1 lists species by common and botanical names) were species from this list that were available from the nursery.

Plants were obtained from the Coeur d'Alene Nursery as 1-year-old bare-rooted plants in the fall of 1973 and 1974. Plants received in October 1973 were heeled in (stored in trenches with roots covered with moist soil) for the winter and planted the following spring. This spring planting consisted of 15,000 plants. An additional 2,500 plants, received in October 1974, were heeled in until planted in November 1974.

Shrubs were planted every 2 feet (0.6 m) in vertical rows 3 feet (0.9 m) apart. The planters used ladders to facilitate planting on steep cut banks in the study areas (fig.2). Hoedads were used to make holes, and any available soil was backfilled around the plants.

Figure 2.—Planting on road cuts using ladders to provide footing for the planter and reduce site disturbance.

Spring planting began in mid-April 1974, and concluded in early May. Climatic conditions during planting were generally good, with the exception of a few warm, dry days during the first week. Snow on some of the slopes created adverse planting conditions by mixing with the soil around the roots of the plants. Conditions during fall planting in November 1974 were adverse; the weather was cold and snowy, and soils were frozen on one site.

The overall condition of the planting stock was very good. Silvery lupine and snowbrush (also called evergreen or shinyleaf ceanothus) plants in both shipments were in poor condition. Saskatoon serviceberry plants received in 1974 were extremely small and in poor condition. Wood's rose plants received in the 1974 shipment were substantially larger than those received in 1973. At the time of spring planting, most of the curl-leaf mountain-mahogany stock was in less than satisfactory condition, possibly due to damage while heeled in.

Survival was based on the percentage of plants living 4 years after planting. Shrubs planted with grass and legumes (described below) were included. Overall planting success was determined subjectively after 9 years. Criteria for this subjective evaluation were based on the work of Nord (1977) and adaptability attributes similar to those of Plummer (1977). These adaptability attributes were used to develop a suitability index similar to that used by Plummer and others (1968). Criteria (rating factors) for the suitability ratings were: **survival**, based upon first- and fourth-year evaluations; **growth**, based on size and spatial development typical for the species; **vigor**, based on flowering frequency and appearance; **natural spread**, based on type of regeneration and degree of plant spreading; and **soil stabilization**, based upon observed holding capabilities and the extent of root systems.

Flowers, vegetative color, and form can add to the visual acceptability of revegetated road cuts. These factors are especially significant in high use areas. Although not included with the above criteria, some evaluations of visual acceptability are included in the Results and Discussion section.

Shrubs and Forbs with Grasses and Legumes

On three road cuts shrubs were planted, as described above, along with a grass and legume mixture, a fertilization treatment, and a straw mulch treatment in the spring of 1974. For these tests seven shrub species and a seeding mixture used by the Flathead National Forest were used (appendix 2). The seeding mixture was applied with a cyclone seeder in a single application at a rate of 13 lb/acre (14.6 kg/ha). (Rates for each species are given in appendix 2.) Fertilizer was applied in a single application with a cyclone seeder at a rate of 250 lb/acre (280 kg/ha) of 16-20-0 (40 lb/acre [44.8kg/ha] actual nitrogen and 50 lb/acre [56kg/ha] actual phosphorus). A randomized block design (Steel and Torrie 1960) was used, giving 12 experimental units or treatment combinations. More details of the treatments and methodology are given in appendix 2.

Ground cover was sampled for each plot 4 years after planting, using ten 20- by 50-cm quadrats on each plot. Analysis of variance procedures were used to evaluate treatment differences.

RESULTS AND DISCUSSION

Survival

Of the 18 species of plants used in this study, six (Wood's rose, red-osier dogwood, thimbleberry, blackcap, bush penstemon, and lovely penstemon) showed good survival (47 percent or more) 4 years after planting (table 1). These species show promise for road cut revegetation in western Montana and northern Idaho. Four other species (redstem ceanothus, spirea, ninebark, and snowbrush) did well in some rating categories but not in others. The other eight species exhibited poor survival and growth or poor growth and rooting characteristics.

Initial survival (assessed at the end of the first growing season) was $\geq$ 70 percent for six species (Wood's rose, red-osier dogwood, blackcap, thimbleberry, black chokecherry, and blue elderberry). Of these, red-osier dogwood, Wood's rose, and blue elderberry exhibited survival rates $\geq$ 87 percent. Low survival rates were noted for silvery lupine (2 percent), ocean-spray (8 percent), and snowbrush (24 percent).

Survival was evaluated in 1978, 4 years after transplanting (table 1). Red-osier dogwood, Wood's rose, and thimbleberry maintained 70 percent or better survival. Black chokecherry and blackcap survival dropped to about 55 percent after the first year, and blue elderberry survival dropped to 30 percent. For most species, losses were sustained primarily during the first growing season, and less than 20 percent loss occurred in following seasons.

A number of factors influenced survival and plant development. Seed source, or origin of plant materials, is one factor. Seed source may have had an effect on the results of this study, but since plant materials were limited, testing for the effect of source was not possible. General location of seed source is given by National Forest in appendix 3.

Planting condition also influenced survival. One cut bank was planted during unseasonably warm spring weather and another was planted during snowstorms on frozen soil in the fall. Severe slumping occurred on both sites and resulted in much mortality. Slumping was not related to planting conditions. First-year survival for Wood's rose was good on both sites (77 percent on spring site and 61 percent on fall site); bush penstemon had good survival (50 percent) on the fall site. First-year survival for all other species was substantially lower than for the average of all other sites. Subsequent losses for established plants of all species on these sites were similar to other cut banks, suggesting that once plants become established under adverse conditions they continue to survive. Survival for cuts on the new road was similar to that on the 20-year-old road.

Aspect appeared to be a significant factor in the survival of lovely penstemon, redstem ceanothus, and spirea (fig. 3). Survival of these species was significantly lower on the western aspect than on either the southern aspect or the eastern aspect. Perhaps high solar energy late in the day causes added moisture stress. Species on the eastern and southern aspects had similar survival rates. Aspect differences might play a more significant role in survivability at lower elevations and in regions with less precipitation than the study sites.

Browsing by wildlife or livestock did not influence survival on these trials. Although elk and deer are in the area, few plants show signs of browsing. Grazing can be a factor in survival of plantings, depending on the forage value of the plants used and the availability of forage in the surrounding area.

Precipitation data obtained from Hungry Horse Dam 5 miles (8 km) south of the study area and stations in the study area showed that precipitation was nearly

Table 1. — Species average survival 4 years following planting

Species	Total number planted	Spring planting 1974	Fall planting 1974	All plantings
		Percent		
Wood's rose	1,424	93	62	82
Red-osier dogwood	93	94		94
Thimbleberry	59	73		73
Saskatoon serviceberry	1,515	68	12	46
Black chokecherry	1,401	65	25	53
Spirea	473	57	45	57
Blackcap	64	55		55
Lovely penstemon	674	36		36
Bush penstemon	411		51	51
Ninebark	134	60	22	49
Blue elderberry	31	30	50	32
Redstem ceanothus	1,534	32	14	26
Smooth sumac	88	20	14	17
Black elderberry	23	9		9
Curl-leaf mountain-mahogany	29	7		7
Snowbrush	1,436	11	4	9
Silvery lupine	653	1		1
Ocean-spray	50	2		2

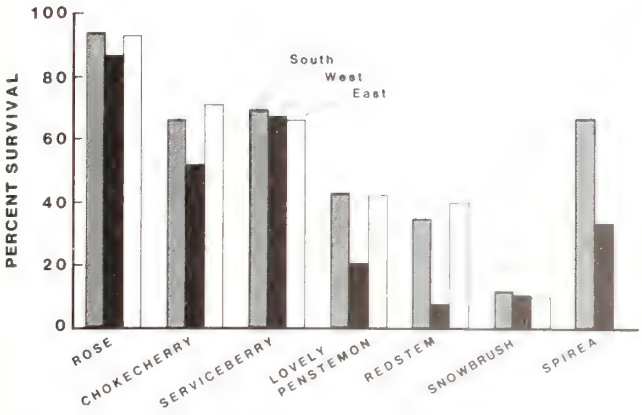

Figure 3.—Overall survival of 4-year-old plants by aspect for those species planted on more than one aspect.

normal from 1974 through 1978, with two exceptions. August 1974 had 1.13 inches (2.87 cm) less rain than normal, which could have contributed to lower initial survival for some species. May through August 1976 had 4.5 inches (11.43 cm) more rain than normal, which could have only been beneficial for plant development.

Mold on the roots and poor plant condition were the primary causes of poor survival of snowbrush (9 percent), silvery lupine (1 percent), and redstem ceanothus (24 percent). Where individuals of these species became established they did reasonably well, which suggests that these species might be useful for site revegetation if stock was improved. A lack of nitrogen-fixing bacteria in these species may have contributed to plant failure. Inoculating plants with rhizobium bacteria may improve plant survival.

Curl-leaf mountain-mahogany stock was in poor condition at the time of planting. It was necessary to discard most of the plants, and of the few planted, survival reached only 7 percent by 1978. Poor plant quality and site disturbance after planting appear to be the most plausible explanations for the low survival rate. Plants that became established remained in good condition after 9 years (fig. 4), even though this species is out of its natural range in the study area.

Initial survival of blue elderberry, black elderberry, and smooth sumac was fair to good, but after 4 years only 30 percent of the plants were still alive. After 9 years only one elderberry plant could be found. Factors influencing species mortality appeared to be the hot, dry slopes and the unfertile rocky soil.

Ocean-spray was expected to perform well on the test sites, but both initial and 4-year survival rates were low (4 percent after 4 years). Unhealthy nursery stock and poor soils may have been responsible for mortality.

Figure 4.—A healthy 9-year-old curl-leaf mountain-mahogany plant provides a protective surface covering and a good root system to hold soil. This plant is 4 feet (1.2 m) tall and 3.5 feet (1.0 m) wide.

Growth

As a measure of success for road cut stabilization and visual enhancement, transplants were expected to grow and spread to provide adequate ground cover and be noticeable from roadways. After 9 years, Wood's rose, bush penstemon, and lovely penstemon were the only species reaching or even approaching their potential size at all planting sites (figs. 5, 6, and 7; table 2). Many Wood's rose plants grew to a height of 3 feet (0.9 m) or more and branched or spread horizontally 2 feet (0.6 m) in radius from the planting. Bush penstemon, a low-growing, mat-forming plant, reached or exceeded its expected size on many of the sites, attaining a basal diameter of up to 4 feet (1.2 m) (fig. 6). Lovely penstemon, a slightly taller plant (without the basal mat-forming tendencies) (fig. 7), reached its expected potential, attaining heights of 2 feet (0.6 m) and diameters of 2 feet (0.6 m), even though this site is out of its natural range. Red-osier dogwood developed well (fig. 8), but not with site uniformity. On several sites, these plants reached heights of 6 feet (1.8 m) and branched well, approaching the maximum size for this species. Plants on the drier cut banks did not develop as well, reaching heights of 3 to 4 feet (0.9 to 1.2 m), but were likely to continue growing. This species did much better than expected on these sites. Red-osier dogwood is generally known as a moist-site plant and to grow and survive as well as it has on these south aspects is surprising.

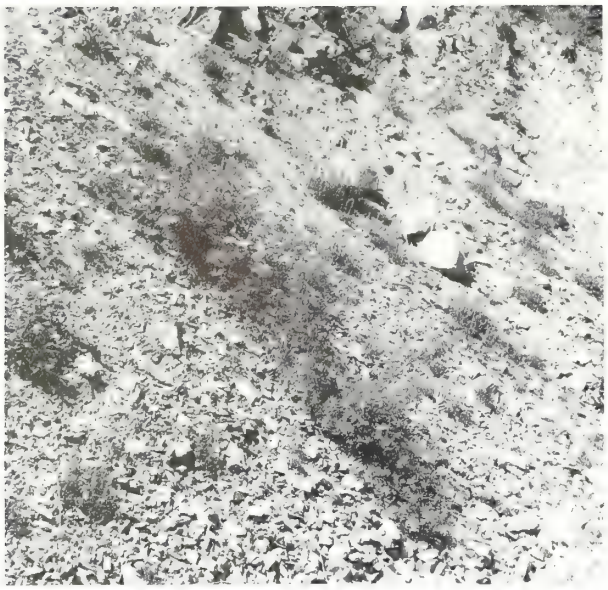

Figure 5.—A row of 7-year-old plants of Wood's rose showing how plants have branched out by sprouting. This presents a very effective ground cover with the ability to hold soil on this rocky road cut. Plants are about 4 feet (1.2 m) tall and 4 feet (1.2 m) wide.

Figure 6.—Six-year-old bush penstemon plants have expanded to form dense mats 3 feet (0.9 m) in diameter with attractive flowers. Soil on the steep bank is effectively stabilized.

Figure 7.—Lovely penstemon on a rocky road cut has expanded and holds loose soil material. Branching is more loosely arranged without forming mats. Flowers are produced frequently and resemble those on bush penstemon. Many new seedlings are established from seed. This site is out of the native range of this species.

Figure 8.—A 9-year-old red-osier dogwood on a steep south slope provides good ground cover and stabilization. Crowns spread to 6 feet (1.8 m) wide and 4 feet (1.2 m) tall and are quite attractive.

Species	Location	Elevation	Microsite	Moisture soils	Foliage	Height	Root type	Flowers	Forage quality	Propagation	Success	Reference
						Feet						
Wood's rose	Inland NW	Low to high	Open to light shade	Dry to moist	Deciduous	1-4	Rhizomes	Small showy pink	Fair	Seeds vegetative	Excellent	Mason and others 1973 Monsen, Christensen 1975 Plummer and others 1968 USDA 1974 USDA 1937 Hitchcock, Cronquist 1973
Bush penstemon	Inland NW	Low to high	Open slopes	Dry, rocky	Evergreen	1-2	Rootstalks	Large showy lavender	Fair	Seeds layering	Good	Plummer 1977 Plummer and others 1968 Davis 1952 Hitchcock, Cronquist 1973 USDA 1937
Lovely penstemon	NE Oreg. SE Wash. N Idaho	Low to mid	Open slopes	Dry, rocky	Evergreen	1-2	Rootstalks	Large showy lavender	Fair	Seeds layering	?	Davis 1952 Hitchcock, Cronquist 1973
Red-osier dogwood	Northern North America	Low to high	Open to shaded	Moist good soils	Deciduous	5-20	Fibrous "root crown"	Small white	Fair to good	Seeds layering	Good	Mason and others 1973 Plummer 1977 USDA 1974 Hitchcock, Cronquist 1973
Blackcap	Widespread in U.S. & Canada	Lower	Open to open woods	Moist good soil	Deciduous	5-7	Rootstalks	Small	Fair to poor	Seed layering	?	USDA 1974 Hitchcock, Cronquist 1973
Thimbleberry	Widespread western U.S.	Sea level to subalpine	Open to wooded	Dry-rocky to moist loams	Deciduous	2-3	Rhizomes	Large showy	Poor to fair	Vegetative	?	USDA 1937 Hitchcock, Cronquist 1973
Redstem ceanothus	Coastal to inland NW	Low to mid	Open to open woods	Moist	Deciduous	3-10	Fibrous "root crown"	Showy	Good to excellent	Seed	Variable	Hitchcock, Cronquist 1973 USDA 1974 USDA 1937
Spirea	Widespread western U.S.	Sea level to subalpine	Open to wooded	Dry to moist	Deciduous	1-3	Rhizomes	Showy	Poor to fair	Vegetative	?	USDA 1937 Hitchcock, Cronquist 1973

Redstem ceanothus (fig. 9), spirea, and thimbleberry developed well on selected sites, but, overall, plants remained small (table 3). Black chokecherry and Saskatoon serviceberry exhibited lackluster development. Both plants averaged 1½ to 2 feet (0.5 to 0.6 m) tall except on eastern aspects where some plants reached heights of 3 to 4 feet (0.9 to 1.2 m). No black chokecherry or Saskatoon serviceberry plants reached sizes typical for their species.

Blackcap plants reached typical size (5- to 7-foot [1.5- to 2.1-m] canes) on some sites. Overall, blackcap did well on south aspects. Other species, except silvery lupine and snowbrush, did not increase in size or vigor. Those few plants of silvery lupine and snowbrush that became established on these slopes did attain typical size.

Vigor and Natural Spread

Ground cover and soil stabilization were enhanced when test species spread via vegetative propagation or seedling establishment. Two indices of these attributes were plant flowering and the presence of new plants. The ability to flower and reproduce also indicates good vigor and health. Of the 18 species used during this study, Wood's rose, bush penstemon, and lovely penstemon excelled in these types of development at most of the planting sites. Wood's rose plants increased by sprouting from the roots, to the extent that it became difficult to distinguish individual plants. The proliferation of flowers (fig. 10) and fruits observed on these plants indicate that establishment of new plants from seed may also occur.

Bush penstemon and lovely penstemon spread through seedling establishment. Bush penstemon plants on several sites flowered prolifically, displaying attractive lavender flowers (fig. 6). New bush penstemon plants were discovered on the cuts (fig. 11), in the ditch, and on the shoulder and fill banks across the road from planting sites (where plants were not present prior to planting). Lovely penstemon seedlings were restricted to the cut banks.

Spirea and blackcap flowered regularly on some planting sites and spread, although to a limited extent,

Figure 9.—A healthy 9-year-old redstem ceanothus plant on this steep south-facing road cut stabilizes the soil and protects the surface. The plant is 4 feet (1.2 m) tall and wide.

Table 3. — Species suitability ratings

Species	Initial survival	Final survival[1]	Growth	Vigor[2]	Natural spread	Soil stabilization[3]	Composite rating[4]
Wood's rose	9	9	9	8	10	10	55
Bush penstemon	6	9	10	10	10	8	53
Lovely penstemon	5	8	10	10	8	8	49
Red-osier dogwood	10	10	8	9	2	8	47
Blackcap	8	6	7	8	7	8	44
Thimbleberry	8	9	5	5	4	6	37
Redstem ceanothus	5	6	8	7	2	8	36
Spirea	6	9	5	4	5	4	33
Ninebark	6	8	5	5	0	4	28
Snowbrush	2	4	6	6	2	8	28
Blue elderberry	10	3	2	5	0	6	26
Black chokecherry	7	8	2	2	0	2	21
Saskatoon serviceberry	6	8	2	2	0	2	20
Smooth sumac	5	4	4	4	0	3	20
Curl-leaf mountain-mahogany	4	2	4	5	0	4	19
Silvery lupine	1	5	5	3	0	2	17
Black elderberry	5	2	2	2	0	2	13
Ocean-spray	1	2	2	2	0	2	9

[1]Final survival based on percentage of initial survivors alive after 4 years.
[2]Based on flowering growth rate and appearance.
[3]Based on root system and observed holding power.
[4]Ratings for each factor are based on a scale from 0 to 10, with 10 being the best.

Figure 10.—Wood's rose plants have attractive flowers and provide a protective soil covering

Figure 11.—Bush penstemon plants grow on rocky sites and spread by seed. New plants are located in the ditch and to the side of the original rows. Closeness of plants in the row demonstrates plant expansion and new plants. A good ground cover that is effective in stabilizing soils is produced.

on sites where it was able to establish well. Blackcap exhibited vegetative spread quite similar to that of Wood's rose. None of the other species successfully regenerated by seed or root propagation.

Soil Stabilization

As previously discussed, growth and natural spread contribute to stabilization of soils on the cut banks Surface coverage exhibited by Wood's rose (fig. 4) and the mat-forming bush penstemon (fig. 10) protect the surface and hold the soil against water and wind. These plants can grow on, survive on, and enhance the appearance of very rocky sites (fig. 12). Root type and depth are important for holding deeper layers (table 2). Plants with rhizomes, such as Wood's rose, blackcap, thimbleberry, and spirea, may function better in holding soil than plants with other types of root systems. Wood's rose and blackcap plants developed extensive rhizomes on the study sites. This was not observed for thimbleberry or spirea. Root systems for lovely and bush penstemons were well developed and seemed to hold soil well on these steep cut banks. Other species, such as red-osier dogwood, redstem ceanothus, and snowbrush, develop deep root systems and provide good stabilization where plants grow well.

Suitability Ratings

Overall assessment of species suitability was based on survival, growth, vigor, natural spreading, and soil stabilization. Species were ranked according to these factors (table 3). Wood's rose achieved the highest ranking, with bush penstemon and lovely penstemon second and third and red-osier dogwood fourth. Wood's rose scored well in all categories, indicating good potential for cut bank stabilization. Red-osier dogwood achieved a high ranking because of its high survival

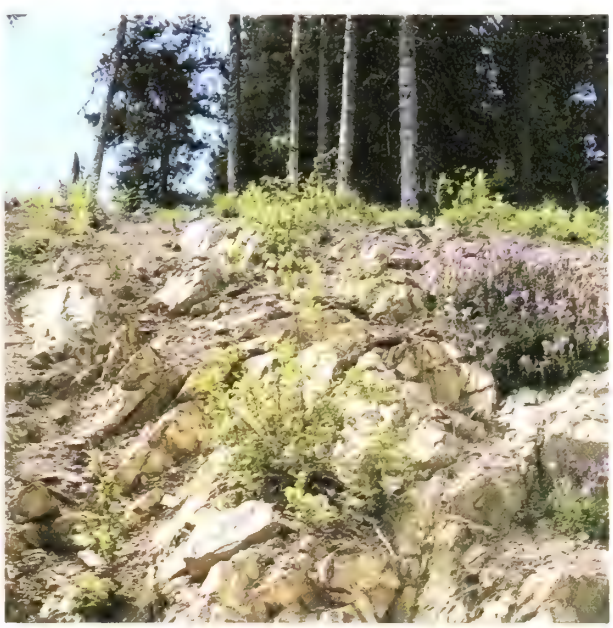

Figure 12.—Appearance of this rocky road cut is improved by flowering bush penstemon, Wood's rose, and black chokecherry plants. These plants have persisted for 9 years with good growth.

rates, but it did not show evidence of natural spreading. Red-osier dogwood, though it performed surprisingly well, cannot be assumed to be as well adapted to the study sites as both penstemons. Both penstemons

achieved as favorable a rating as Wood's rose in all areas of consideration except survival. (The survival rate of the penstemons was ≃ 50 percent, which could probably be improved through better nursery stock and planting techniques.)

Survival rates of black chokecherry, Saskatoon serviceberry, and ninebark were good on some sites; however, poor or mediocre performance of these species in other rating categories, particularly size increase, affected their standing in the overall ranking of test species. Poor soil conditions and the harsh site environment were the most probable factors affecting plant growth, although the extremely small size of the plants received for the second planting also influenced plant development.

Blackcap, spirea, and thimbleberry were considered suitable for selected sites due to good survival rates and moderate growth. Redstem ceanothus did well in all categories except survival and natural spread. Survival may be enhanced if problems with planting stock were overcome.

Grasses, Legumes, and Shrubs

The results of using grasses, legumes, and fertilizer in conjunction with shrubs at selected sites were as expected. Plots with no treatment sustained a ground cover of 2 to 18 percent at the end of 4 years. Fertilized plots had 4 to 25 percent cover. Those plots seeded with grasses and legumes produced a cover of 9 to 44 percent. The highest average ground cover resulted on plots treated with grasses, legumes, shrubs, and fertilizer. Analysis of variance showed that grass and fertilizer significantly influenced ground cover on only one cut bank. Differences were not significant at other sites. The appearance of the banks with grasses, legumes, and shrubs was much better than those with bare soils (fig. 13).

Survival rates for shrubs planted on plots seeded with grasses and legumes were as good or better than for shrubs planted alone. Planting grasses and legumes resulted in rapid development of ground cover and protection against surface erosion while shrubs took root. Birdsfoot-trefoil grew well, and provided an attractive cover of prolific yellow blooms on all the seeded cut banks (fig. 13). Seed crops were good, as evidenced by the spreading and regeneration of new plants in areas where it was not seeded. Smooth brome-grass and orchard-grass also did well, especially on fill bank sites.

Figure 13.—Grasses and legumes form a good ground cover on this south slope 6 years after planting. The area to the left in the photo was not seeded or planted. Birdsfood-trefoil produced numerous attractive yellow flowers and spread naturally by seed.

CONCLUSIONS

Planting of native shrubs proved to be an effective means of revegetating road cuts in northwestern Montana. Once established, esthetically pleasing flowers contributed to the overall suitability of the shrub plantings, while unattractiveness of many species as forage insured their continued growth.

Of the species studied, Wood's rose demonstrated the best survivability and regeneration characteristics, even on harsh sites. These findings concur with those of Mason and others (1973), documenting the growth of this species on severe road cuts in the Northern Region of the Forest Service.

Bush penstemon and lovely penstemon exhibited good potential for use in revegetation. Spreading, regeneration, and adaptability to both dry and moist sites were excellent. Plummer (1977) and Monsen and Christensen (1975) also found bush penstemon adaptable to sites within the Intermountain Region.

Several other species studied grew well, indicating their usefulness in site revegetation. Species in this category included thimbleberry and blackcap on south aspects; redstem ceanothus and spirea on east aspects. Red-osier dogwood did exceptionally well on south aspects, considering that this species is a riparian shrub.

Mechanized planting methods are available for steep road cuts, but may not be cost effective unless large areas are treated. Hand planting and seeding techniques will be very useful and quite effective where it is necessary to revegetate road cuts or steep slopes on a small scale. Hand-planting techniques are also more easily adapted to fit the users' needs.

A further concern is the availability of native shrubs and seeds. Commercial nurseries can provide some species, but special arrangements for seed collection and propagation of other species may be necessary. Advanced planning is necessary to select adapted species and assure good condition of stock at planting time. This planning can go a long way toward insuring the ultimate success of a revegetation project.

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APPENDIX 1: COMMON AND BOTANICAL NAMES OF SPECIES

Common name	Botanical name[1]
Blackcap	*Rubus leucodermis* Dougl.
Black elderberry	*Sambucus racemosa* ssp. *pubens* var. *melanocarpa*
Blue elderberry	*Sambucus cerulea* Raf.
Black chokecherry	*Prunus virginiana* var. *melanocarpa* (Nels.) Sarg.
Silvery lupine	*Lupinus argenteus* Pursh
Curl-leaf mountain-mahogany	*Cercocarpus ledifolius* Nutt.
Mallow ninebark	*Physocarpus malvaceus* (Greene) Kuntze
Ocean-spray	*Holodiscus discolor* (Pursh) Maxim.
Bush penstemon[2]	*Penstemon fruticosus* (Pursh) Greene var. *fruticosus*
Lovely penstemon[2]	*Penstemon venustus* Dougl. ex Lindl.
Redstem ceanothus	*Ceanothus sanguineus* Pursh
Red-osier dogwood	*Cornus stolonifera* Michx.
Saskatoon serviceberry	*Amelanchier alnifolia* Nutt.
Snowbrush	*Ceanothus velutinus* Dougl.
Spirea	*Spiraea betulifolia* Pall.
Smooth sumac	*Rhus glabra* L.
Thimbleberry	*Rubus parviflorus* Nutt.
Wood's rose	*Rosa woodsii* Lindl.
Alta tall fescue	*Festuca arundinacea* Schreb.
Manchar smooth brome	*Bromus inermis* Leys.
Orchard-grass	*Dactylis glomerata* L.
White Dutch clover	*Trifolium repens* L.
Birdsfoot-trefoil	*Lotus corniculatus* L.

[1]Nomenclature is after Hitchcock and Cronquist 1973.

[2]Identifications were made by Peter F. Stickney, Forest Service, Intermountain Forest and Range Experiment Station, Forestry Sciences Laboratory, Missoula, Mont.

APPENDIX 2: TREATMENTS USED IN GROUND COVER EVALUATIONS

Treatments and Levels

Fertilizer

1. None
2. 250 lb/acre (280 kg/ha) of 16-20-0

Grass-legume seedings

1. None
2. Grass and legume mixture seeded without straw mulch
3. Grass and legume mixture seeded with straw mulch

Shrubs planted

1. None
2. Seven species[1] were used

The above treatments were applied using all 12 combinations and replicated once on one cut bank and twice on two cut banks. One cut bank was east-facing and the other two faced south. All of these cuts were along the new road. Fertilizer treatment amounted to approximately 40 lb/acre (44.8 kg/ha) of available nitrogen and 50 lb/acre (56 kg/ha) available phosphorus as a one-time application. Twelve plots at each replication were 27 to 48 feet (8.2 to 14.6 m) wide and length went from the road to the top of the cut bank. Seeding and planting were done in April and May 1974. No fall seedings were used. Ground cover evaluations were made in 1978 using a 7.9- by 19.7-inch (20- by 50-cm) plot frame. Ten samples were taken on each plot to obtain average cover for the plot. Analysis of variance procedures were used to test for treatment differences.

[1] Wood's rose, Silvery lupine, Black chokecherry, Saskatoon serviceberry, Redstem ceanothus, Snowbrush, Lovely penstemon

Grass and legume mixture

Species	Seeding rate	
	lb/acre	*kg/ha*
Alta tall fescue	2.5	2.8
Manchar smooth brome	4.0	4.5
Orchard-grass	2.5	2.8
White Dutch clover	2.0	2.2
Birdsfoot-trefoil	2.0	2.2

APPENDIX 3: SEED SOURCE FOR PLANTS RECEIVED FROM THE COEUR D'ALENE NURSERY

Species	Location
Blackcap	Coeur d'Alene National Forest
Black elderberry	Coeur d'Alene National Forest
Blue elderberry	Coeur d'Alene National Forest
Black chokecherry	Coeur d'Alene and Okanogan National Forests
Silvery lupine	Okanogan National Forest
Curl-leaf mountain-mahogany	Montana
Ninebark	Lolo National Forest
Ocean-spray	Coeur d'Alene National Forest
Bush penstemon	Lolo National Forest
Lovely penstemon	Idaho
Redstem ceanothus	Idaho
Red-osier dogwood	Coeur d'Alene National Forest
Saskatoon serviceberry	Idaho
Snowbrush	Okanogan National Forest
Spirea	Coeur d'Alene National Forest
Smooth sumac	Colville National Forest
Thimbleberry	Okanogan National Forest
Wood's rose	Kootenai National Forest

Hungerford, Roger D. Native shrubs: suitability for revegetating road cuts in northwestern Montana. Research Paper INT-331. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1984. 13 p.

Four years after planting, Wood's rose (82 percent), red-osier dogwood (94 percent), and thimbleberry (73 percent) had the highest survival of the 18 species of native shrubs planted on steep road cuts in northwestern Montana. Two penstemon species and Wood's rose demonstrated good growth and regeneration 9 years after planting. Several of the species tested can be valuable for revegetating road cuts, stabilizing slopes, and improving their appearance. Species suitability is rated and important attributes are given for the species that rated the highest.

KEYWORDS: revegetation, soil stability, road cuts, shrubs

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Volume and Biomass For Curlleaf Cercocarpus in Nevada

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RESEARCH SUMMARY

Volume and biomass equations were developed for curlleaf cercocarpus (*Cercocarpus ledifolius* Nutt.) in the Egan and Schell Mountains near Ely, NV. Fifty-two trees were sampled to measure cubic foot volume. Diameter at root-collar (DRC) was used to develop a simple linear volume prediction equation for individual trees. Volume predictions can be converted to biomass by wood density factors reported from the study. A ratio equation was developed to predict volume and biomass for various utilization standards. A method was developed for obtaining bark volume and biomass.

The jackknife technique was used to assess the reliability of the equations. This technique allowed computation of confidence intervals for predictions from several equations used in a series. The 95 percent confidence intervals (expressed as a percentage of the predicted value) were generally less than 20 percent of predicted volume and biomass for curlleaf cercocarpus trees within 2-inch diameter classes.

Volume and Biomass For Curlleaf Cercocarpus in Nevada

David C. Chojnacky

INTRODUCTION

The Resources Planning Act (RPA) of 1974 calls for assessment of all forest and rangeland, including shrubby woodlands. Curlleaf cercocarpus (*Cercocarpus ledifolius* Nutt.), with the former common name of curlleaf mountain-mahogany, a woodland tree found mainly in Nevada and Utah, is included. In addition to its wood fiber value, it is an important browse plant for wildlife and has root modules that fix nitrogen. This study sought to develop volume and biomass prediction equations for cercocarpus to provide foresters with tools needed to assess woodlands.

In anticipation of changing inventory and management needs for cercocarpus, I developed equations and methods to obtain the following:

1. Gross volume and [illegible] for a 1.5-inch minimum branch diameter and with the capability to vary [illegible].
2. Gross volume and [illegible] with the capability to vary [illegible].
3. Volume and biomass [illegible].

Volume was expressed in cubic feet and biomass in pounds according to current USDA Forest Service Forest Survey standards.

PREVIOUS WORK

Numerous ecological studies have been conducted on cercocarpus, but few studies include methods to estimate wood volume or biomass. Whittaker and Niering (1975) evaluated biomass of hairy cercocarpus (*C. breviflorus*) in the Santa Catalina Mountains of Arizona. They developed a stem-wood volume equation from 15 trees (with average diameter 3.26 cm):

$$V = 6.03 + 0.2939 D^2 H$$

where:

V = volume of stem wood (cm³)
D = basal diameter (cm) at 10 cm above ground line
H = total tree height (m)

R. O. Meyer (personal communication, 1980) did some preliminary work on biomass estimation of cercocarpus in the Snake Range of Nevada. He identified crown diameter, the number of stems greater than [illegible], and basal diameter 6 inches above ground line as potential variables to predict biomass. Weaver (1979) developed biomass equations for cercocarpus and other shrubs in Montana. He [illegible] to total biomass in a single equation, applicable to sagebrush, cercocarpus, dogwood, ninebark, bitterbrush, sumac, buffaloberry, and [illegible].

[illegible]

where:

BM = total aboveground biomass (kg)
A = 3.14 MNR MNR
MNR = [illegible]
MNR = minimum plant radius (cm)

Research has indicated that diameter, height, number of stems, and crown size should be considered as potential predictor variables of cercocarpus volume. For this study, these and several other variables were measured on trees.

DATA COLLECTION METHOD

Data were collected at three locations in the Egan Mountains and five locations in the Schell Mountains near Ely, NV (fig. 1). Trees were selected arbitrarily by [illegible] diameter classes. Diameter measurement was made at the root-collar (DRC) at ground line. At each location, one or two trees in each diameter class were sampled, totaling 52 trees in diameter classes ranging from [illegible] to 22 inches. Tree heights ranged from [illegible] to 21 ft.

The following variables were measured for potential volume and biomass prediction:

1. DRC to nearest 0.1 inch
2. Diameter at breast height (d.b.h.) to nearest 0.1 inch
3. Total tree height to nearest foot
4. Crown diameter maximum and minimum to nearest foot
5. Number of stems at 20 percent of tree height
6. Number of stems greater than 3 inches in diameter at 4.5 ft

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[illegible]

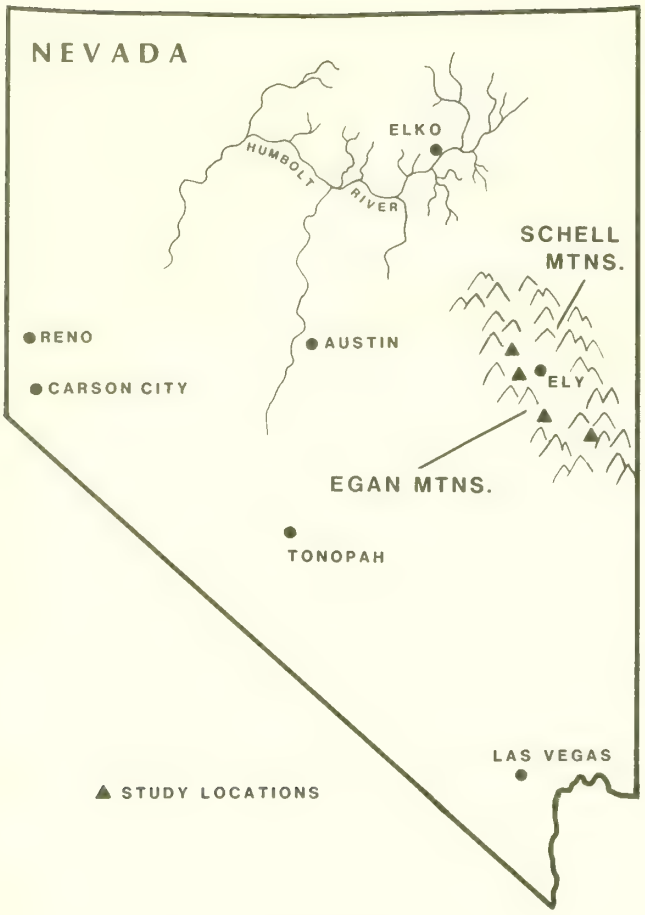

Figure 1.—Study locations were in the Schell and Egan Mountains.

If the tree stem forked at the the point of measurement, I computed an equivalent diameter (Meeuwig and Budy 1981):

$$\text{Equivalent diameter} = \sqrt{\sum_{i=1}^{n} D_i^2}$$

where:

D_i = DRC of the ith stem.

n = number of stems at measurement point (DRC or d.b.h.).

Stems smaller than 1.5 inches in diameter were not included in the DRC and d.b.h. measurements.

The trees were cut into segments from 1 to 5 ft long to measure diameter and length, depending on stem forks and taper of the segments. Although the intent was to keep segment taper less than 15 to 20 percent, average taper was 23 percent on the 1,122 segments measured.

I made outside bark diameter measurements (to the nearest 0.1 inch) at each segment's large end, midpoint, and small end. These were used to compute volume.

I recorded percent of internal defect for each segment and identified segments containing all dead wood. Limbs severed from the trees were also included as dead wood. These were fairly common, apparently due to a heavy wet snowfall the spring prior to sampling.

Three segments from each tree were subsampled fo a cross-sectional disk 2 inches thick. These disks we from the top, midsection, and butt of each tree and were used to determine specific gravity and inside ba diameter for biomass computation.

DATA ANALYSIS AND RESULTS

I used the segment data to compute volume and biomass for the trees, developed methods to predict volume and biomass, and assessed the reliability of th prediction methods.

Computation Volume and Biomass

To develop prediction models, volume and biomass of the wood and bark were required for each tree (for variable mbd's). Volume computations were done sep rately for wood and bark combined, and for wood alone. The volume computations were converted to biomass using wood density factors. Defective and dead wood was also examined.

Wood and bark volume, to a 1.5-inch mbd, was computed for each tree using Newton's log formula (Husch and others 1972, p. 122) on each segment, an then segment volumes were summed. In some cases the segment measurements were inadequate for computing tree volume to an mbd larger than 1.5 inches. These cases required an estimate of segment length. I used a geometric scheme to estimate an unknown segment length when the desired mbd fell somewhere between the segment's large and small diameter measurements. I calculated the unknown segment length from the known segment length and known diameters, assuming segment shape to be a cone:[2]

$$X = L \left(\frac{\text{mbd-SD}}{\text{LD-SD}} \right) L$$

where:

L = known segment length

X = unknown segment length

SD = small diameter of a segment

LD = large diameter of a segment.

In this fashion wood and bark volumes to variable mbd's of 2, 3, 4, 5, 6, 7, and 8 inches were computed using Newton's formula and the length approximation (X) when necessary.

Wood volume was computed by first converting the outside bark segment diameter measurements to inside bark diameter. I used a regression relationship developed from a subsample of segments (fig. 2):

$$IBD = -0.1501 + 0.93613(OBD)$$

where:

IBD = inside bark diameter (inches)

OBD = outside bark diameter (inches).

The same procedure used for wood and bark volume computation was also used for computing wood volume I also computed volumes to variable mbd's from 2 to 8 inches.

[2] A comparison of mean volumes computed for 1,122 segments using Newton's formula versus a cone frustrum formula showed a 0.14 percent difference; hence, the conic assumption is reasonable.

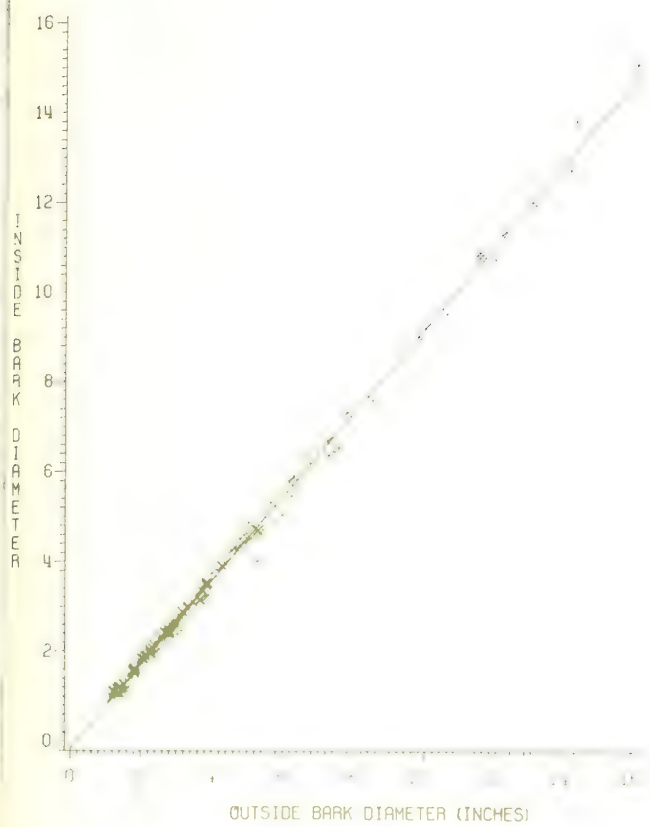

Figure 2.—Inside bark diameter plotted against outside bark diameter with the regression equation

(table 2). For fuelwood management, dead cercocarpus limbs are just as valuable as live material because the wood is usually sound; hence, there is probably no net volume reduction.

Predicting Volume and Biomass

I developed equations to predict gross cubic foot volume and cubic foot wood biomass by variable-sized trees. I developed separate equations for wood and bark. I omitted discussion about equations for cubic foot wood. An explanation follows for the two equations for cubic foot volume: a variable-sized equation (wood and bark in this) and a bark in this.

I selected a simple linear equation predicting volume from DBH. Combinations of the variables height, crown diameter, and number of stems were examined for predicting volume, but none proved to be much better than the equation based on DBH. Diameter at breast height (DBH) is easy to measure and is usually the most important factor affecting volume. Variables that are not consistent because of their measurement are incompatible with current woodland inventory procedures.

Because the relationship of volume to DBH is not linear, the volume equation was developed using a natural log transformation and simple linear regression. The S_{yx} and S_{yx} (Log BIAS) positive correction of percent for prediction of mean volume instead of median volume that results from application of log transformation (Beedlow and Pienaar 1981).

I also developed another equation to predict volume to variable minimum branch diameters. Burkhart (1977) derived a factor for folidely-pine, ratio of volume to a specified upper stem diameter divided by total volume as a function of DBH and upper stem diameter. In this study, a ratio of wood volume (ft³) divided by total volume (ft³) was regressed against the log transformations of DBH and upper stem diameter (table 3).

Biomass equations were not developed because the best measure of accuracy obtainable within the study design was a conversion of volume to biomass using a constant wood density factor for all trees. Volume equations in table 3 can be converted to biomass equations by use of the appropriate wood density factor in table 1.

Table 1.—Density and specific gravity for curlleaf cercocarpus wood and bark

Component	Density	Mean	95 percent confidence[1] interval	Range	Sample[2] size
	Lb ft⁻³	*Specific gravity*			
Bark and wood	43 68	0 70	± 0.025	0.55-0 89	36
Wood	50 54	81	± .022	70- 94	36
Bark	22 46	36	± .019	29- .48	36

[1]The average specific gravity for curlleaf cercocarpus is expected to lie within the confidence interval unless a 1-in-20 chance has occurred in selecting the samples. The confidence intervals were based on the t-statistic, 11 degrees of freedom, and variances jackknifed by deleting one tree at a time.

[2]Samples are from 12 trees, but each tree was sampled at the top, midpoint, and butt.

Table 2.—Dead volume expressed as a percent of gross wood and bark volume to a 1.5-inch minimum branch diameter (mbd) and wood volume to a 1.25-inch mbd

Diameter class (DRC in inches)	Percent dead wood and bark	Percent dead wood	Percent sampling error[1]	Sample size
2	0	0	—	2
4	0	0	—	6
6	0	0	—	6
8	.3	.3	±38.9	6
10	2.3	2.1	±68.6	7
12	1.8	1.7	±98.6	6
14	2.7	2.5	±65.4	6
16	8.8	8.5	±106.7	5
18	8.1	7.8	±77.9	4
20	4.3	4.0	±377.1	3
22	11.0	10.4	—	1

[1]The sampling error is for wood and bark values (it is roughly the same for wood). Sampling error is expressed as a percentage of the average percent dead and implies the true value for percent dead lies within the sampling error unless a 1-in-20 chance has occurred in sample selection. The large sampling errors are due to the small sample sizes and due to data that are distributed both discretely and continuously.

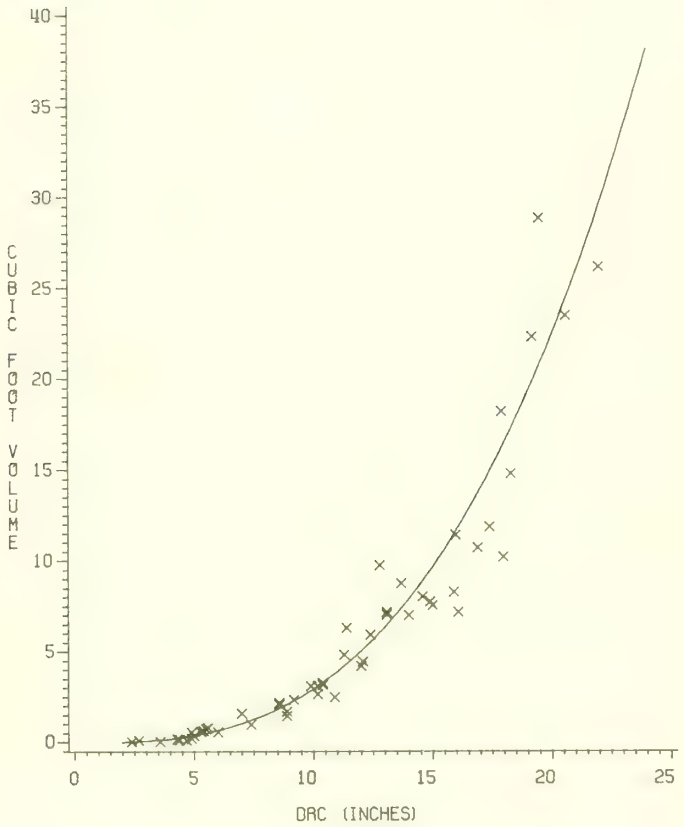

Figure 3.—Wood and bark volume data plotted against DRC, with the volume equation overlaid.

Table 3.—Equations for predicting curlleaf cercocarpus wood fiber products

Product	Equation	Equation #	R^2
Cubic foot volume of wood and bark to a 1.5-inch mbd	$V = 0.00356(DRC)^{2.920}$	(1)	0.96
Cubic foot volume of wood to a 1.25-inch mbd	$V = 0.00258(DRC)^{2.964}$	(2)	.96
Mbd ratio for wood and bark	$R = 0.6281 + 0.23875 \ln^1(DRC) - 0.47745 \ln(mbd)$	(3)	.78
Mbd ratio for wood	$R = 0.5210 + 0.25729 \ln(DRC) - 0.46192 \ln(mbd)$	(4)	.75

[1]ln is the natural log function.

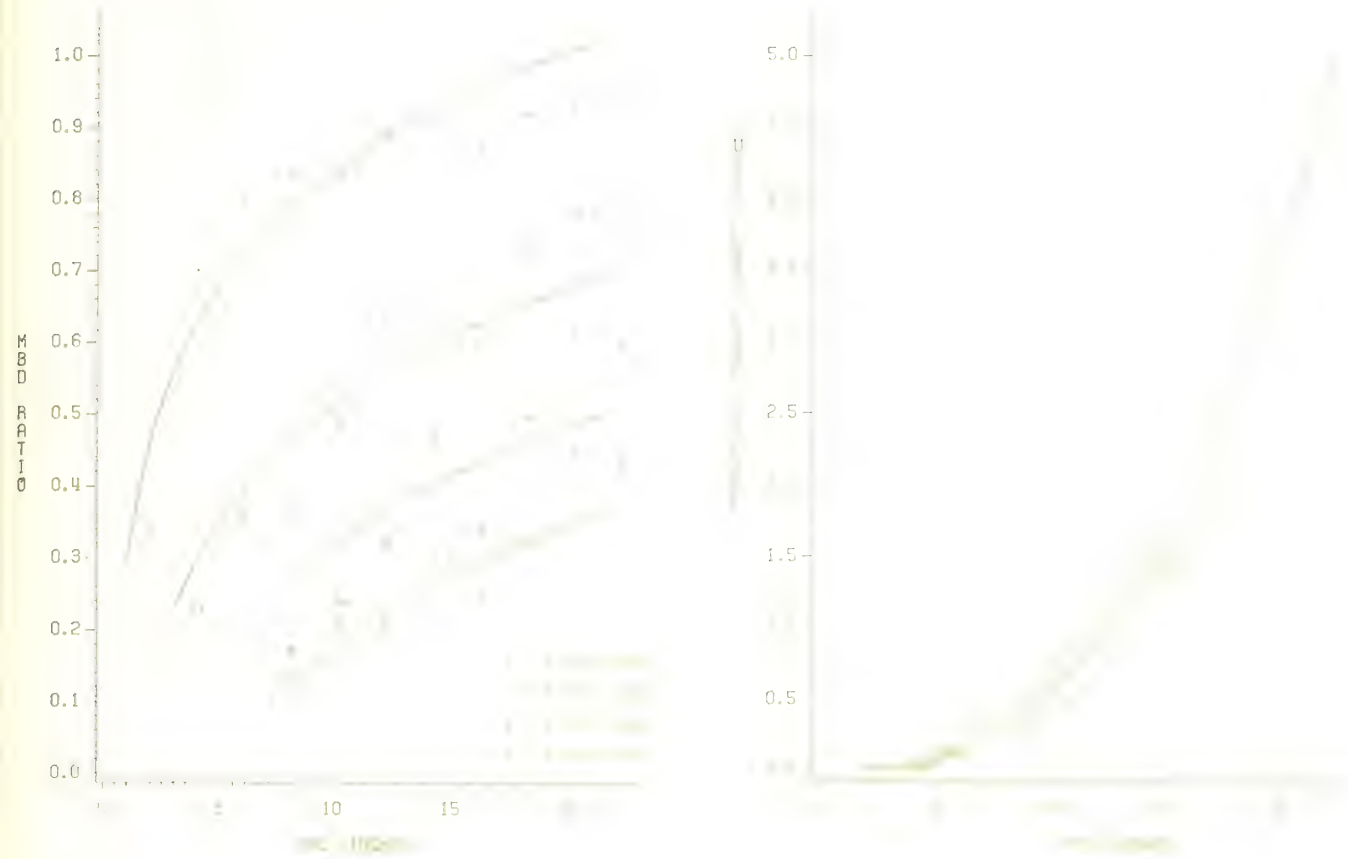

Figure 4 — The means within ... of mbd volume to total ... The correspondin...

Bark ... tractin... and bark ... bark ... method ... other ...

In summary, the ... density ... and ... provides a guide and an example for computing ...

Table 4.—A guide to use the equations in table 3 and wood density factors in table 1 for the estimation of curlleaf cercocarpus wood volume and biomass

Product to be estimated	Wood and/or bark	Wood
Volume	Eq.(1)	Eq.(2)
Volume to a variable mbd	Eq.(1) × Eq.(3)	Eq.(2) × Eq.(4)
Biomass	Eq.(1) × wood and bark density	Eq.(2) × wood density
Biomass to a variable mbd	Eq.(1) × Eq.(3) × wood and bark density	Eq.(2) × Eq.(4) × wood density
Bark volume	Eq.(1) − Eq.(2)	none
Bark biomass	(Eq.(1) − Eq.(2)) × bark density	none
Bark volume and biomass to a variable mbd	none	none

An example for computing wood and bark biomass of a tree to a 4-inch mbd:

Given: DRC 18 inches
mbd 4 inches
wood and bark density 43.68 lb ft (from table 1)

Wanted: Pounds of wood and bark biomass for a 4-inch mbd

Step 1—Compute wood and bark volume for a 1.5-inch mbd

$$\text{Volume} = 0.00356(\text{DRC})^{2.92}$$
$$= 16.48 \text{ ft}^3 \quad (1)$$

Step 2—Compute wood and bark 4-inch mbd ratio

$$\text{Ratio} = 0.6281 + 0.23875 \ln(\text{DRC}) - 0.47745 \ln(\text{mbd})$$
$$= 0.66 \quad (3)$$

Step 3—Compute biomass result

Result = Eq.(1) × Eq.(3) × wood and bark density
= 16.48 × 0.66 × 43.68
= 475 lb of wood and bark for a 4-inch mbd.

Reliability of the Equations

Determining reliability for equations developed in logarithmic units and for systems of equations can be difficult. The R^2 and standard error of regression are in log units and have little meaning for assessing cubic foot volume predictions. However, a technique called jackknifing is useful for estimating variances in complex situations (Mosteller and Tukey 1977; Schreuder and Brink 1983). The jackknife method involves computing a statistic (in this case regression coefficients) from a data set numerous times, each time deleting a different observation(s). Each computation is called a pseudo-value, when subtracted from the statistic using all data points:

$$y^*_j = (k)y_{all} - (k-1)y_{(j)}, \quad j = 1,2,\ldots,k$$

where:

y^*_j = a pseudo-value
k = number of observations
y_{all} = the statistic based on all observations
$y_{(j)}$ = the statistic based on k-1 observations with observation j deleted.

A variance is easily calculated from the pseudo-values:

$$S^2 = \frac{\sum_{j=1}^{k} (y^*_j - \bar{y}^*)^2}{k-1}$$

where:

$\bar{y}^*$ = the arithmetic mean of y^*_j.

Once variances are computed, confidence limits can be calculated using the t-statistic:

$$\bar{y} \pm t_{\alpha, k-1} S / \sqrt{k}.$$

Using the jackknife theory presented above, I computed confidence limits by 2-inch diameter class (DRC) for predictions from three sets of equations: (1) wood and bark volume to 1.5-inch mbd, (2) wood volume to a 3-inch mbd, and (3) wood and bark biomass to a 3-inch mbd. These represent predictions for one, two, and three sets of equations, respectively. The confidence limits were constructed by diameter class because the variance of an estimate increases with tree size, which makes it inappropriate to use an average variance for all tree sizes.

Each jackknifed variance was based on 52 pseudo-values. Each pseudo-value required development of regression equations with one tree missing. The same tree was deleted for all regressions when a pseudo-value was based on more than one equation.

Table 5 contains predictions, percent of actual volumes, and the confidence intervals. Confidence intervals were constructed from jackknifing and expressed as a percent of a prediction. The percent of the actual volumes lies within the confidence intervals most of the time. Also, the confidence intervals were similar whether one, two, or three equations were used, indicating that errors may not increase by using two or three equations in a series.

The small differences between the weighted averages of the actual and predicted values in the last row of table 5 indicate that the equation or systems of equations are best when averaging over all tree sizes. Some individual size classes have quite a large difference between predicted and actual estimates, but these average out when considering totals.

Table 5.—A comparison of actual (actual) percentage errors and [illegible] of predicted values [illegible]

Diameter class (DBC)	Average DBC	Trees	Wood volume in cubic feet to a 1.25-inch mbd			Wood volume in cubic feet to a 5-inch mbd			Wood and bark biomass in pounds to a 3-inch mbd		
			Predicted value	Percent actual value	95 percent C.I.	Predicted value	Percent actual value	95 percent C.I.	Predicted value	Percent actual value	95 percent C.I.
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
9 [illegible]	10.1	[illegible]	210	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
11 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
13 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
15 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Weighted average [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[1] [illegible]

[illegible]

DISCUSSION

The volume and biomass estimation methods given in this study should predict within about 20 percent of the actual values for individual trees. Better results can be expected for averages from a sample of trees. However, these inferences rely on the assumption that future samples of cercocarpus trees will have forms similar to those in this study. This is because the modeling techniques were based on empirical data manipulation with little biological reasoning to warrant extrapolation to other areas. This study, however, could provide insights useful in hypothesis building for future cercocarpus volume modeling research done from a more biological perspective.

Observation of the equations in table 3 indicates cercocarpus volumes may be proportional to DRC cubed. Other people have supported a hypothesis that a function of DRC is proportional to volume or biomass for pinyon-juniper and other woodland trees (Gholz 1980; Tausch 1980; Weaver and Lund 1982; Felker and others 1983).

Perhaps the best use of this study could be an application of the modeling techniques to a subsample of trees in a multistage or multiphase woodland inventory. DRC is the only variable that would need to be measured in the main large sample. Developing new equations for the subsample of trees would require considerable effort in destructive sampling, but a visual sampling method (Born and Chojnacky, in preparation) would alleviate this constraint. Such an application would rely heavily on well-established sampling theory and would shun uncertain equation extrapolations.

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Chojnacky, David C. Volume and biomass for curlleaf cercocarpus in Nevada. Research Paper INT-332 Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1984. 8 p.

Volume and biomass equations were developed for curlleaf cercocarpus (*Cercocarpus ledifolius* Nutt.) in the Egan and Schell Mountains near Ely, NV. The equations predict cubic foot volume of wood and bark for variable minimum branch diameters. Wood density factors are given to convert volume predictions to pounds of fiber biomass. The reliability of the equations was assessed using the jackknife technique to construct confidence intervals.

KEYWORDS: *Cercocarpus*, woodland, jackknife, specific gravity

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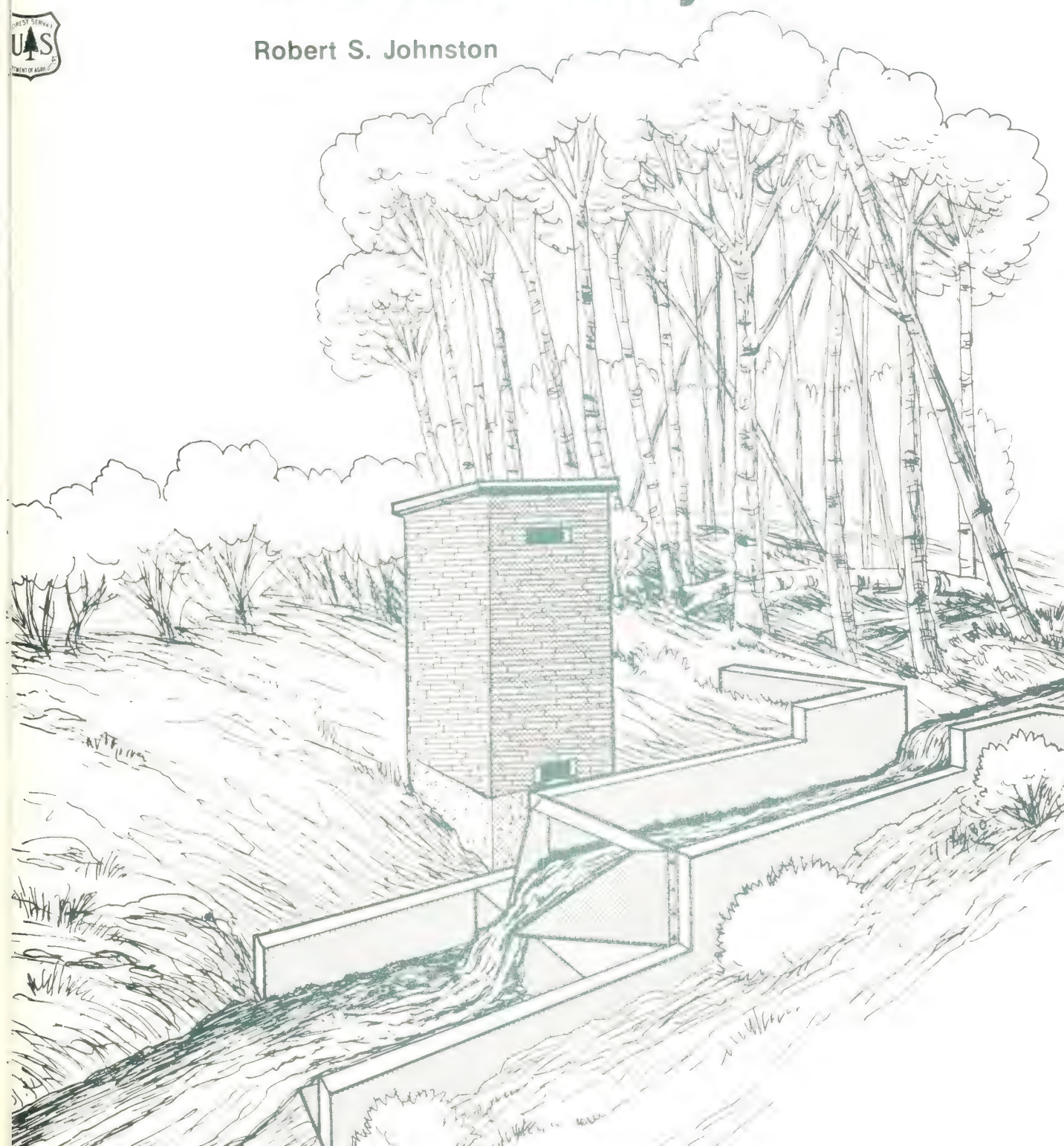
Effect of Small Aspen Clearcuts on Water Yield and Water Quality

Robert S. Johnston



RESEARCH SUMMARY

Streamflow and water quality were monitored in a paired watershed study involving the removal of 20 percent of the aspen (on 13 percent of the area) in five small clearcuts from a 217-acre (88-ha) catchment. There were no significant changes in peak flow, timing, or annual yield during the 4 years of posttreatment monitoring. Significant changes in pH, calcium, magnesium, and nitrates in the snowmelt streamflow from ephemeral subdrainages occurred the second year after cutting. At least some of the differences were attributed to the chemistry of the 1976-77 snowfall, which was also significantly different from snow sampled in the pretreatment period.

ACKNOWLEDGMENT

A major watershed study cannot be conducted over a period of 14 years without the help of many individuals. I am most appreciative to Robert D. Doty, research forester, my co-researcher during most of the study; Ezra Hookano, technician, for his field and laboratory assistances; and Norbert V. DeByle who was project leader and contract officer during the study.

THE AUTHOR

ROBERT S. JOHNSTON has been a research hydrologist with the Intermountain Station for the past 20 years. He has a B.S. in forestry from Rutgers University and has done graduate work in watershed management and hydrology at Colorado State University. He is currently assigned to the mined-land rehabilitation work unit at Logan, Utah. His major research emphasis has been the hydrologic response of aspen management, rehabilitation of alpine disturbances, and erosion and surface runoff associated with mining.

Effect of Small Aspen Clearcuts on Water Yield and Water Quality

Robert S. Johnston

INTRODUCTION

It is generally accepted that removing trees from a watershed affects the hydrologic response of the area, usually resulting in increased streamflow. Even though the potential for water augmentation exists, research results have been inconsistent and there remains a question as to whether sufficient increases can be generated through land management to be detectable downstream in larger drainage systems (Office of Technology Assessment 1983).

The measurement of various streamflow parameters and calibration of paired watersheds provide a necessary and logical approach to testing the hydrologic response of given inputs and management alternatives. Classical watershed studies began in the United States in 1909 at Wagon Wheel Gap, CO, and have been conducted since then throughout the United States and many other countries. Hibbert (1967) reviewed the results of 39 catchment experiments and more recently Bosch and Hewlett (1982) summarized the results of 94 catchment studies to determine the effects of vegetation changes on water yield and evapotranspiration. The general conclusion of these reviews was that the removal of forest cover increases water yield, but that results were not consistent regarding the amount of increase, length of the treatment effect, or the effect on streamflow timing or peak flows. Studies have shown that, in general, increases in streamflow are proportional to the amount of timber removed. Other studies have indicated that streamflow response is also related to the type of precipitation (rain or snow) and its distribution through the year, proximity of timber cuts to stream channels, shape of the watershed, drainage patterns, and soil characteristics.

There are about 5,130,000 acres (2 076 000 ha) of aspen (*Populus tremuloides*) forests in Colorado and Utah (Van Hooser and Green 1983; Green and Van Hooser 1983). Most of this forest occurs on federally managed land in the high-water-yielding mountain zone. Whether the managment of aspen can result in increased water yields remains in question. Even if management of forest lands for water production is not feasible or desirable, the hydrologic impacts of aspen management need to be defined.

Results from several plot studies indicated that 3 inches (76 mm) or more of soil water could be saved by removing deeply rooted aspen, thereby eliminating evapotranspiration losses (Croft and Monninger 1953; Johnston 1969, 1970). Based on these results a paired watershed study was initiated in 1965 on the East and West Branches of the Chicken Creek drainage on the Davis County Experimental Watershed. The purpose of this study was to investigate the effects of small aspen clearcuts on the hydrologic response of a small watershed. Because paired watershed studies are very expensive and time demanding, clearcutting only a portion of the aspen acreage was selected as the initial treatment. It was felt that this treatment would be least destructive and would allow a second treatment (total clearcut, grazing, or prescribed burning) to be studied in the future.

SITE DESCRIPTION

A detailed description of the study area was presented by Johnston and Doty (1972). Briefly,the East and West Branches of Chicken Creek are small adjacent catchments, 137 acres (55 ha) and 217 acres (88 ha), respectively, located in the headwaters of Farmington Canyon, about 14 miles (22 km) northeast of Salt Lake City, UT (fig. 1). These drainages lie within the Davis County Experimental Watershed, established in 1930 to study the causes and prevention of erosion and floods originating in the Wasatch Mountains. Elevation of the Chicken Creek catchments is between 7,500 and 8,400 feet (2 286 and 2 560 m). Side slopes are relatively gentle (12 to 45 percent) and each contains gently sloping grassy meadows in the drainage bottom. The area has been protected from fire and grazing since 1930. Both drainages contained small but active beaver colonies throughout the study.

A variety of soils are found on the watersheds, ranging from deep loamy alluvial soils in the bottoms to deep clayey colluvial soils on side slopes and shallow gravelly loams on the ridges. Soils are generally well drained, with good water-holding capacity. Underlying geologic materials are a complex series of igneous outcrops on the ridges, with metamorphic and sedimentary materials on the side slopes and lower portions of the watersheds.

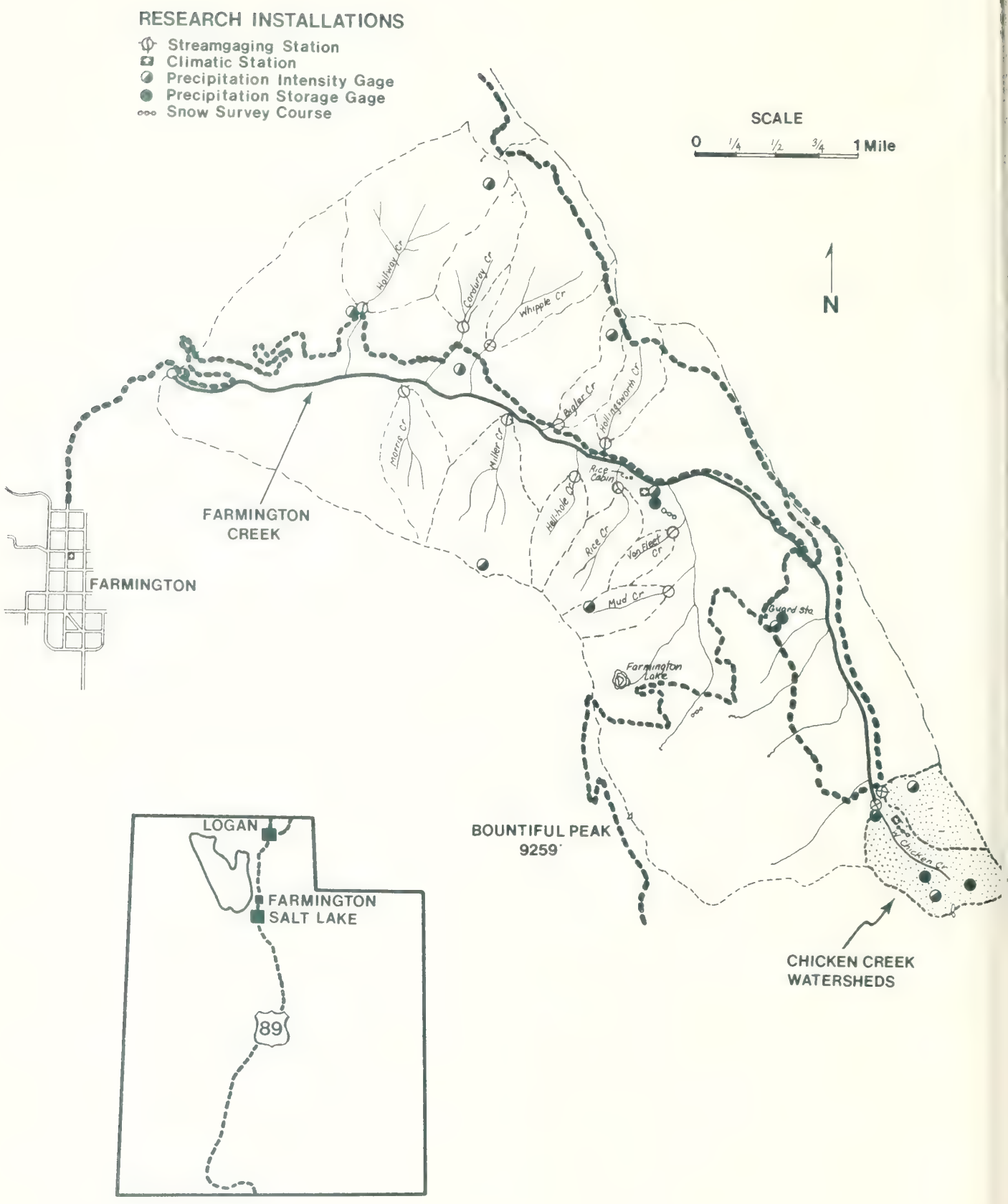


Figure 1.—The Farmington Canyon drainage and Chicken Creek watersheds.

Aspen occupy 63 percent of the East Branch and 66 percent of the West Branch, and they occur throughout the watershed except on the ridgetops and bottom meadows. In 1972, stands had an average age of 32 years, height of 23 feet (7 m), and basal area of 82 ft^2 acre (18.8 m^2/ha). Many of the aspen clones have a distinct two-story canopy, dominated by a few large trees in the 70- to 80-year-old age class and a large number of smaller trees in the 30- to 40-year-old class. These age classes appear to be closely related to the establishment of the Experimental Watershed and protection from grazing. Protection of this area since the 1930's has contributed to a lush understory vegetation composed of a mixture of grasses, forbs, and shrubs that would not normally be found in areas that are grazed or have been recently burned. Most of the remaining area in the valley bottoms and on the ridges is dominated by grass-forb vegetation, along with scattered areas of mountain brush and sagebrush. A small stand of conifers occurs on each drainage (less than 4 percent of the area). A detailed description of the response of aspen and understory to clearcutting was reported by Bartos and Mueggler (1982).

The climate of this study area is probably representative of large areas of midelevation regions in the Intermountain West. Mean annual temperature was a cool 36.6 °F (2.5 °C) and mean summer temperature (July through September) was 56 °F (14 °C). Average annual precipitation is about 45 inches (1 140 mm), 80 percent of which occurs as snow from November through April. Summers are short and dry and rainfall is highly variable. Most summer rainfall occurs as convective thunderstorms fed by prevailing southwest winds carrying moisture from the Gulf of Mexico. Winter weather patterns are largely dominated by frontal systems moving from the Pacific Northwest, but occasionally winter storms move in from the southwest. Average winter temperatures are below 32 °F (0 °C) with occasional periods of subzero (F) temperatures.

The aspen clearcutting and the large amount of inventory data collected provided an opportunity for several other studies of the impacts of this treatment on water and related resources. These included: vegetation response and dynamics (Bartos and Mueggler 1982), stream temperature (Pettee 1976), impervious watershed areas (Pankey 1980), hydrologic modeling response of aspen-conifer succession (Jaynes 1978), water quality (White 1977), biomass and nutrient content of aspen (Johnston and Bartos 1977; Bartos and Johnston 1978), decomposition and nutrient dynamics of aspen litterfall (Bartos and DeByle 1981), effect of harvesting on songbird populations (DeByle 1981), snowshoe hare-cover relationships (Wolfe and others 1982), and feeding and behavior of mule deer and elk (Collins and Urness 1983).

METHODS

A 3-foot (91.4-cm) H-type flume was installed in 1965 at the mouth of each catchment. Streamflow was recorded with analog-to-digital recorders at 15-minute intervals from April through October and at 30-minute intervals during the remainder of the year. Flumes were covered and heated during the winter months to prevent freezing and provide more accurate discharge measurements (Doty and Johnston 1967).

Air temperature, windspeed, wind direction, and relative humidity were monitored in the West Branch watershed beginning in 1971. The precipitation monitoring network consisted of two shielded storage gauges and a shielded intensity gauge; two additional intensity gauges were operated during summer months. Snowfall was monitored at a snow course on the West Branch. In addition, the precipitation monitoring network was supplemented with over 30 years of record from two storage gauges and two snow courses located in Farmington Canyon.

Clearcut

About 20 percent of the aspen, but only 13 percent of watershed area, were removed in five small clearcuts in the West Branch (fig. 2). The cutting units ranged in size from 3 to 10.2 acres (1.2 to 4.1 ha) and totaled 28.2 acres (11.4 ha). Proposed clearcuts were defined using the following criteria based on the pretreatment inventory: (1) vegetation type was predominantly aspen; (2) deep, loamy, colluvial soils; (3) areas with greatest depth of loosely consolidated subsurface material as identified in the seismic survey.

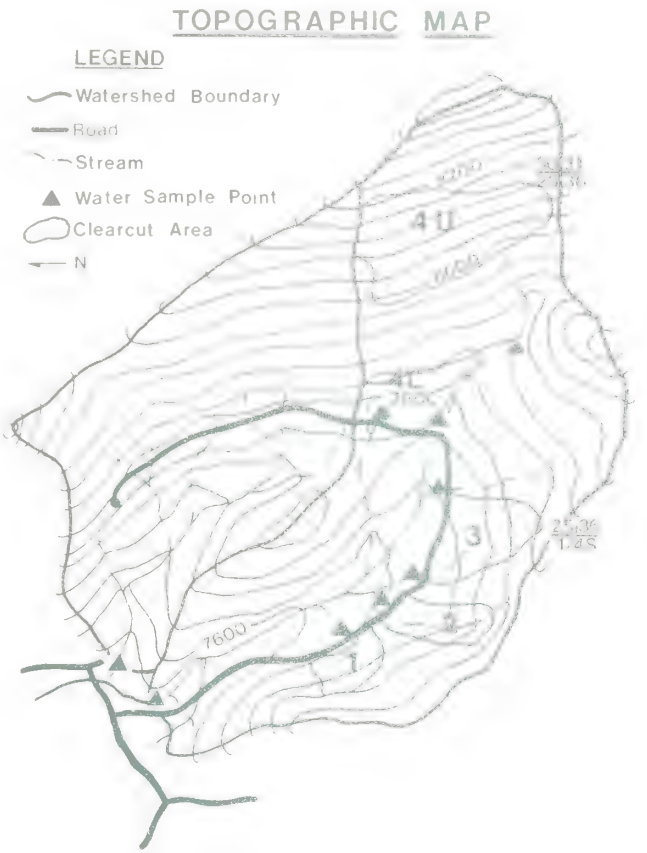


Figure 2.—Topographic map of the East and West Branch watersheds and location of sampling points and clearcut areas.

All aspen greater than 2 inches (5 cm) diameter were cut on all five units. Material suitable for firewood and posts was removed and slash was cut and scattered except unit 4U (fig. 2) where the material was not removed. Most merchantable material was either hand loaded or horse skidded. Vehicle use on the cut areas was minimal. Approximately 62 percent of the area was cut during the summer of 1974 and the remainder in 1975. No access roads were constructed and no work was permitted after the smowmelt season until the area was dry, in order to decrease possibility of surface disturbance and road damage. All cutting was more than 150 yards (137 m) from permanent stream channels.

Water Quality

Water chemistry was monitored at the mouth of each catchment from 1971 through 1976. Water samples were collected at least bimonthly from the beginning of snowmelt until the end of September and monthly during the remainder of the year. In addition, water samples were collected weekly from each of the ephemeral streams draining cutting units 1, 2, and 3 and one uncut drainage adjacent to cutting unit 3. Temperature, pH, and electrical conductivity were measured on site and samples were analyzed for nitrate, phosphorus, potassium, calcium, magnesium, sodium, and bicarbonate using techniques described in "Standard Methods" (American Public Health Association 1971). An automatic event sampler was used to collect samples of rainfall and snow samples were collected at about monthly intervals and analyzed.

Beginning in 1967, bedload and suspended sediment were measured near each flume. Bedload was sampled in a Polyakov-type riverbed sampler installed in each channel. Suspended material was measured from grab samples collected at the flumes.

RESULTS AND DISCUSSION

Water Yield

Mean annual water yield during the calibration period (1966-74 water years) was 136 acre feet (167 754 m^3) from the East Branch and 394 acre feet (485 992 m^3) from the West Branch. The relationship of annual streamflow from the two areas to each other and to annual precipitation is shown in figure 3. Annual yield is closely related to annual precipitation, which is dominated by snowfall accumulation. About 88 percent of annual flow from both watersheds occurs during the snowmelt period of April, May, and June. Although streamflow from the two drainages is highly correlated, hydrologically the two areas are dissimilar. Analyses of flow records indicate that average water yield from the West Branch was 46 percent of annual precipitation compared to 25 percent yield from the East Branch. Most of this disparity is due to the unequal distribution of snow on the two catchments. For example, a snow-depth contour map of peak snow accumulation during the 1972-73 season showed substantial areas of deep drifting along the southeast boundary of the West Branch and wind scour across the northeast boundary of the East Branch. This distribution pattern indicated about a 30 percent greater snow depth on the West Branch than was calculated from the snow course and storage gauge data, assuming a fairly uniform snowfall distribution.

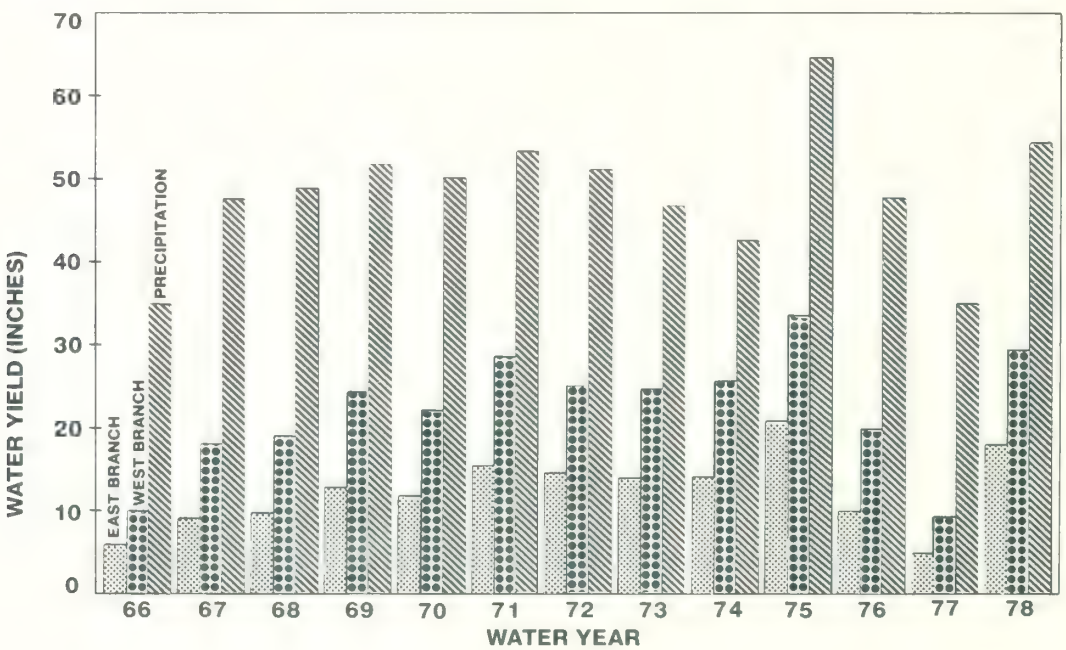


Figure 3.—Comparison of annual streamflow from the East and West Branches of Chicken Creek and annual precipitation.

Streamflow from the West Branch was calibrated against flow from the East Branch for 9 years (1966-74) prior to clearcutting. Annual flows from the two catchments and the regression line are plotted in figure 4. Regression analysis of pretreatment annual flows had an R^2 of 0.97, with a standard error of 1.18 inches (30 mm). Both precipitation and annual streamflow varied greatly during the 4 years of posttreatment monitoring. Annual yield from both watersheds exceeded the maximum and minimum flows previously recorded. These flows were in response to the extreme high and low snowfall amounts in 1975 and 1977, which resulted in the maximum and minimum annual precipitation, 65 and 35 inches (1 650 and 890 mm), respectively (table 1). The predicted yields, using the regression shown in figure 4, were higher than measured yields for 3 of the 4 years after clearcutting; average predicted yield for all 4 years was about 1 inch (2.54 cm) greater than measured. Covariance analysis indicated no significant change in posttreatment total annual flow due to clearcutting (P=0.05). Past research has indicated that increases in water yield associated with timber harvest occur either during the peak stream flow period or, more frequently in arid and semiarid areas, during low flow periods. Analysis of peak flows and seasonal flows during both the snowmelt and low flow periods also showed no significant changes after cutting.

Figure 4.—Relationship of annual streamflow (inches) for the East and West Branch watersheds.

Table 1.—Observed and predicted water yield from the West Branch following clearcutting

Year	Precipitation	Annual yield	Predicted yield	Net change
		Inches		
1975	64.73	33.59	37.29	-3.70
1976	47.64	19.80	18.15	1.65
1977	35.00	9.14	9.38	- .24
1978	54.20	29.66	31.72	-2.06
Average	50.39 (128 cm)	23.05 (58 cm)	24.14 (61 cm)	-1.09 (-3 cm)

Several studies of changes in soil water depletion following removal of deeply rooted aspen (Croft and Monninger 1953; Johnston 1969, 1970) indicated that up to 3 inches (76 mm) of soil water could be saved by reduced transpiration loss. If this water became available as streamflow on the West Branch, the resulting increase in flow would have been about 7 acre feet (8 635 m^3), based on the area cut. This increase was not detected, indicating that linear extrapolation of predicted water increases to area of cut did not apply on Chicken Creek.

Subsequent to this research, recent analyses of results from many watershed studies throughout the United States and other countries have led to the conclusion that removal of less than 20 percent of the forest stand will not result in a detectable increase in water yield (Bosch and Hewlett 1982; Evans and Patric 1983). Results from Chicken Creek, where 13 percent of the watershed area (20 percent of the total aspen area) was clearcut, further confirm this premise. In another Utah study, however, streamflow was increased by up to 4 inches (102 mm) by removing all aspen from a watershed (Robinson 1973). Robinson's results substantiate estimates of potential increases in water yields indicated by the earlier plot studies and show that these increases may be realized when a sufficiently large area is treated.

Average yield from the West Branch during the peak flow period was 13.55 inches (344 mm), nearly twice as great as the East Branch (fig. 5). Flows from both watersheds were very similar during the remaining months. Peak flow during the snowmelt runoff period (April-May) accounts for 86 percent and 88 percent of total runoff for the East and West Branches, respectively. The clearcuts did not appreciably affect snow distribution on the area. The snowmelt rate was observed to be higher in openings than in the adjacent aspen stands, but the change in melt rate for these small areas was not sufficient to cause a detectable shift in the snowmelt hydrograph.

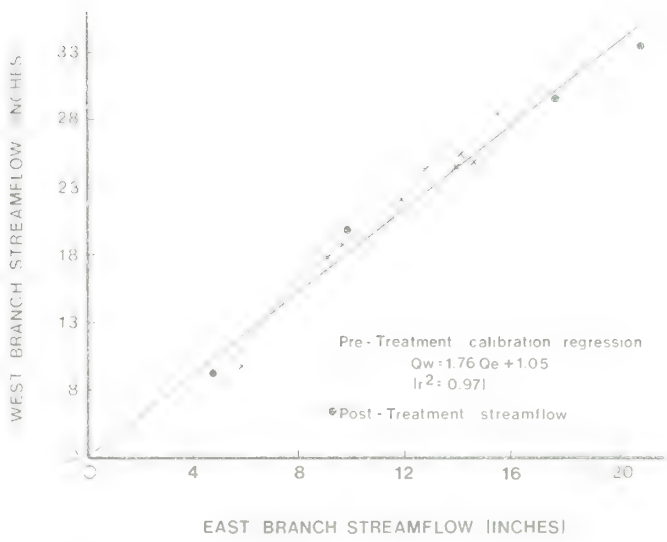


Figure 5.—Distribution of average monthly streamflow prior to clearcutting.

Vegetative Response

The Chicken Creek clearcutting provided an opportunity to investigate the effect of cutting on understory production, community dynamics, and aspen sprouting. Vegetation was inventoried prior to cutting and for 3 years after cutting (Bartos and Mueggler 1982). As expected, clearcutting stimulated aspen sucker production. The average number of suckers increased from 930 per acre (2 300/ha) before cutting to 17,806 per acre (44 000/ha) 2 years after cutting. There also was a significant increase in all understory vegetation following clearcutting, including a general increase in the proportion of shrubs and a decrease in the proportion of forbs. Understory production increased from 900 pounds per acre (1 009 kg/ha) to nearly 2,700 pounds per acre (3 026 kg/ha). It has been suggested that transpiration from these nearly one-half million new aspen suckers and 25.4 tons (23 metric tons) of increased understory biomass may have mitigated some of the water savings realized by cutting the aspen overstory. This response, however, was not noted in the earlier plot studies of soil water depletion following removal of aspen.

Water Quality

The low amounts of both suspended and bedload sediments measured during the pretreatment calibration period indicate good quality water and generally low erosion rates in both watersheds. Average bedload production was only 0.07 and 1.14 pounds per acre per year (0.08 and 1.28 kg/ha) from the West and East Branch, respectively. These materials were primarily sand and gravel, with about 8 percent organic material. Suspended sediment production was also low in both watersheds. The maximum recorded was 135 p/m for the West Branch and 48 p/m for the East Branch, with average suspended sediment of 16 and 6 p/m, respectively. Peak sediment concentration occurred during peak snowmelt runoff and occasionally during rainfall runoff events. Sediment production was influenced by the network of beaver dams in both drainages. These dams and their current state of repair or disrepair respond as either sinks or sources of sediment. Sediment measurements were not continued into the treatment and posttreatment period because it was felt that any treatment effect on sediment production would be masked by the beaver dams. Much of the difference in bedload production between the two drainages is attributed to an abandoned beaver dam above the East Branch gauging station. Also, because of the method of skidding and location of clearcuts away from permanent stream channels, the clearcuts were not expected to contribute significantly to sediment production.

Water Chemistry

Water samples were collected during the spring snowmelt runoff period from ephemeral streams draining cutting units 1, 2, 3, and an uncut control subdrainage located adjacent to unit 3. Samples were collected weekly for 2 years prior to cutting (1973 and 1974) and 2 years after cutting (1975 and 1976). There were significant differences in pH, Ca, Mg, and NO_3 between the pretreatment period and second year following cutting within each drainage (table 2). There were also significant increases in these same parameters from the control drainage, indicating that changes were influenced by factors other than the clearcutting.

Analysis of snow samples collected in April 1976 indicated substantial increases in all four parameters from the previous 3 years' snow samples, suggesting the possibility that changes were due at least in part to differences in precipitation chemistry for that year.

Ionic concentrations from each of the subdrainages were quite different from each other and most were significantly different (95 percent level) from ion concentrations of water samples collected at the mouth of the watershed (White 1977). Diagrammatic illustrations of ion concentration (fig. 6) show that most differences are in the Ca and Mg concentrations, which in turn affect the pH, conductivity, and alkalinity values. Concentrations of Ca and Mg are highest from unit 1 and become progressively lower from subdrainages farther up the watershed. White (1977) attributed these differences to the discontinuity in soil types between the subdrainages. Soils in unit 1 are entirely of shale and siltstone origin; soils in unit 2 are partially shale and siltstone and partially a schistose loam. The remaining subdrainages, unit 3 and the control, which have markedly lower Ca and Mg concentrations, have deep colluvial soils (Johnston and Doty 1972). This relationship was confirmed by White by examining ion concentrations of water soluble extracts from soil columns collected from each of the areas.

Table 2.—Average values of several water chemistry parameters from subdrainages the second year after cutting (b) that were significatly different from precutting values (a)

Parameter		Cut 1	Cut 2	Cut 3	Control
pH	a	7.47	7.49	6.99	6.90
	b	7.93**	7.88**	7.39**	7.11*
Ca mg/L	a		30.78	11.65	14.31
	b		23.01*	8.11**	3.92**
Mg mg/L	a		5.11	2.66	4.43
	b		4.10**	2.09*	1.23*
NO_3 mg/L	a			.04	.06
	b			.11*	.08*

** – Significant at 0.95 percent level or higher.
* – Significant at 0.85–0.95 level.

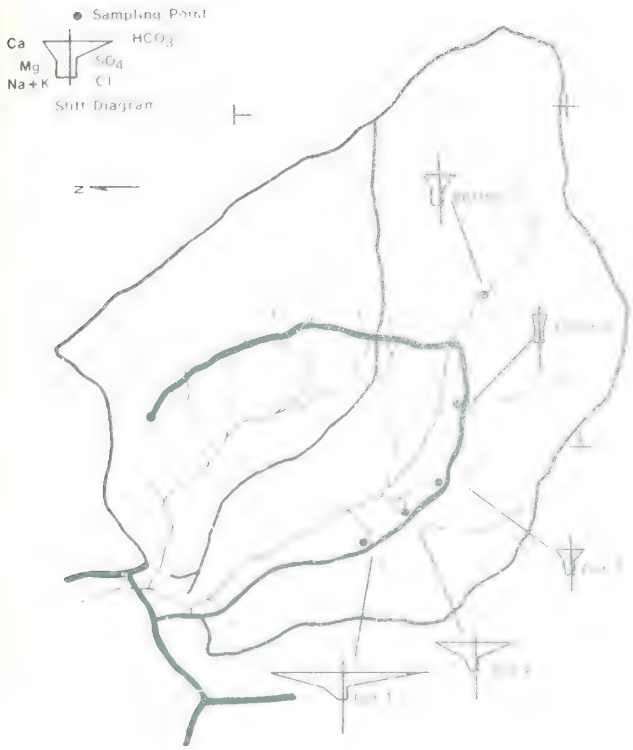


Figure 6.—Variation of major ion concentrations between tributaries in the West Branch watershed, spring 1973 (from White 1977).

Water chemistry from the adjacent East and West Branch watersheds is also quite dissimilar (table 3). In his study, White (1977) concluded:

> The Chicken Creek waters are quite dilute neutral to slightly alkaline solutions containing primarily calcium, magnesium, sodium, potassium, bicarbonate, sulfate, and chloride. Nitrate and phosphate are present at much lower concentrations. The dynamics of the solution are controlled by the $CO_2/CO_3/HCO_3$ equilibrium system. Within the limits of these stated characteristics the waters are extremely variable. The variability can be seen over time and from location to location. The annual chemical budgets indicate that the watersheds are suffering a net loss of all chemical constituents, except nitrate and phosphate . . . . The West Branch watershed not only produces almost twice as much water per unit area, but the water is more chemically concentrated.

Variations in chemistry of these waters are attributed to differences in parent material and soil texture between the subdrainages. Additional causes of variation are the unequal inflow of ions caused by the unequal distribution of snow accumulation on the catchments. Snowmelt water frequently flows overland from rapidly melting snowpacks directly into an ephemeral drainage system and is rapidly delivered to the main stream channel.

As expected, most water quality parameters fluctuated widely throughout the year. Conductivity and pH dropped sharply during peak flows and reached their highest levels during periods of low flows. The highest concentrations of calcium, magnesium, sodium, bicarbonate, and chloride also occurred during low flow periods. Sulfate and potassium concentrations, on the other hand, were highest during the snowmelt period. Nitrate and phosphorus were low throughout the year. Concentrations of potassium, sulfate, chloride, and sodium were highest throughout the year from the East Branch, while the pH, conductivity, and concentrations of carbonate, calcium, and magnesium were highest from the West Branch (table 3).

Table 3.—Comparison of water quality parameters measured between 1971 and 1976 (about 138 samples)

Parameter	East Branch			West Branch		
	Mean	Min.	Max.	Mean	Min.	Max.
pH	7.4	6.4	8.9	7.2	6.4	8.0
Conductivity (μmhos)	158.0	95.0	238.0	119.0	55.0	163.0
Total alkalinity (mg/L)	67.0	32.0	139.0	44.0	16.0	84.0
Calcium (mg/L)	20.7	6.5	36.0	11.3	3.5	32.0
Magnesium (mg/L)	4.2	1.3	8.2	3.5	1.0	9.8
Sodium (mg/L)	5.4	1.8	12.8	7.0	0.7	14.0
Potassium (mg/L)	9	.1	3.4	.8	.01	4.0
Phosphorus (mg/L)	1	< .01	6	03	01	.4
Nitrate (mg/L)	1	< .01	7	.08	< .01	.4
Sulfate (mg/L)	5.5	< .01	10.7	6.6	< .01	12.0
Total hardness (mg/L)	69.0	30.0	114.0	42.0	12.8	103.0
Chloride (mg/L)	4.8	1.0	12.4	5.0	1.9	9.0

No measurable effects of clearcutting on water chemistry were detected at the mouth of the West Branch watershed. This result is supported by other studies in the Western United States (Sopper 1975; Swanson and Hillman 1977; Fredrickson 1971). Several possible reasons for this lack of chemical response have been suggested. It may reflect the small percentage of area cut and the minimal disturbance during logging, distance of the cuts from main stream channels, deep soils, and possibly low biological activity associated with low annual temperature and low summer precipitation. Although these possibilities are speculative, they are supported by other studies (Brozka and others 1981; Nicholson and others 1982).

Precipitation Chemistry

Chemical analysis of precipitation samples collected between 1972 and 1975 shows considerable variability between storms and between rain and snow events. Both snow and rain tend to be slightly acid, with the 4-year average pH level slightly over 5 (table 4). The pH of individual events varied from 7.7 to a very acid 3.0. In recent years acid rainfall has caused considerable environmental damage and raised concern in the United States, particularly in the Northeast. Acid precipitation also occurs in Utah. One rainfall event at the study site was sufficiently acid (pH 3.0) to destroy the metallic moisture sensing grid on the automatic rainfall collector. Unlike major areas of the Eastern United States, soils in the study area, being generally deep and largely derived from sedimentary material, are capable of buffering acid rain and snowfall.

In general, rain contained higher concentrations of the anions and cations tested than snow. Weather patterns associated with individual storms were not documented during this study. There appears to be a relationship between storm patterns and precipitation chemistry. There are two chemically different types of storms in the area those with low pH and high NO_3 and SO_4 concentrations and those with high pH and high Ca, Mg, and Na concentrations. This may be explained by the variability of storm patterns that affect the study area. Both winter and summer storms can originate from systems either from the Pacific Northwest or the Southwest. Storms from the Southwest move across the highly populated and industrial Salt Lake Valley before reaching the study area and are presumed to be higher in nitrates and sulfates. Storms approaching from the west and northwest move across vast areas of semidesert and the Great Salt Lake, from which they can pick up and enter large amounts of various salts into the storm system.

CONCLUSION

Removing deeply rooted aspen from 13 percent of a 217-acre (88-ha) watershed had no significant effect on the streamflow timing, peak flow, or annual streamflow yield. Similarly, there were no significant changes in streamflow chemistry attributed to cutting from the catchment or from the ephemeral streams draining the individual cutting units. The lack of measurable effects from harvest may be attributed to the small size of the area cut and the minimal disturbance during cutting. Also, some treatment effects may have been masked by the network of beaver dams in the catchment.

The study does emphasize two important principles: (1) anticipated water yield increases should not be simply extrapolated to the area of harvest and (2) the extrapolation of precipitation measurements, particularly snow, to areal distribution and the subsequent calculation of water yield can lead to serious errors, especially in mountainous terrain.

Table 4.—Comparison of rain and snow chemistry (1972–75)

	pH	Conductivity	HCO_3	Ca	Mg	Na	K	P	NO_3	SO_4	Cl
		μmhos	*mg/liter*								
Rain	5.7*	33	3.80	3.50	0.42	2.07	0.77	0.05	0.43	2.50	1.66
Snow	5.3	12	4.10	1.90	0.23	0.62	0.36	0.02	0.29	1.10	1.07

* Mean values.

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Johnston, Robert S. Effect of small aspen clearcuts on water yield and water quality. Research Paper INT-333. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1984. 9 p.

Streamflow and water quality were monitored in a paired watershed study involving the removal of 20 percent of the aspen (on 13 percent of the area) in five small clearcuts from a 217-acre (88-ha) catchment. There were no significant changes in peak flow, timing, or annual yield during the 4 years of posttreatment monitoring. Significant changes in pH, calcium, magnesium, and nitrates in the snowmelt streamflow from ephemeral subdrainages occurred the second year after cutting. At least some of the differences were attributed to the chemistry of the 1976-77 snowfall, which was significantly different from snow sampled in the pretreatment period.

KEYWORDS: hydrology, aspen, *Populus tremuloides*, water yield, water quality

The Intermountain Station, headquartered in Ogden, Utah, is one of eight regional experiment stations charged with providing scientific knowledge to help resource managers meet human needs and protect forest and range ecosystems.

The Intermountain Station includes the States of Montana, Idaho, Utah, Nevada, and western Wyoming. About 231 million acres, or 85 percent, of the land area in the Station territory are classified as forest and rangeland. These lands include grasslands, deserts, shrublands, alpine areas, and well-stocked forests. They supply fiber for forest industries; minerals for energy and industrial development; and water for domestic and industrial consumption. They also provide recreation opportunities for millions of visitors each year.

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